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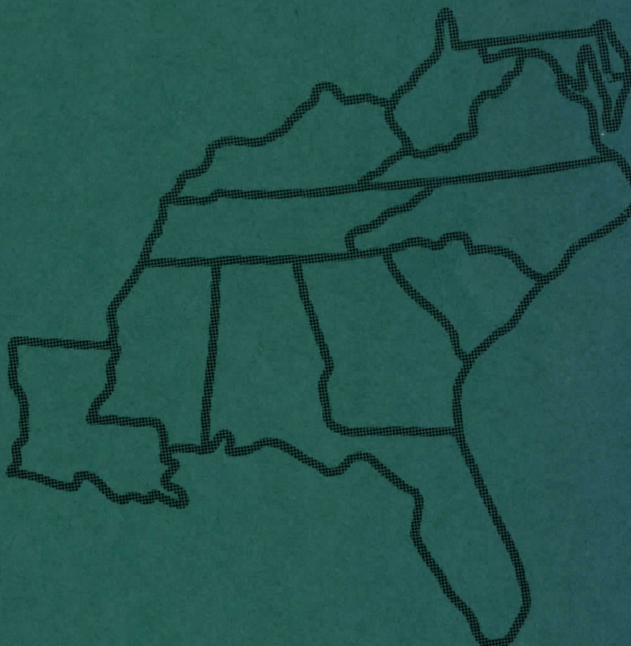

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THE CLAY MINERALS OF A TRAVERSE ON THE NORTH CAROLINA CONTINENTAL MARGIN AND BERMUDA RISE

By

P. Michael Terlecky
Duke University

ABSTRACT

Semiquantitative mineral analysis of the < 2 micron size fraction of eighteen gravity cores from the North Carolina Continental Margin and Bermuda Rise reveals that montmorillonite and illite are the dominant clay minerals with kaolinite and chlorite constituting most of the remainder of the total clay fraction. Quartz, feldspar, and mixed-layer material are also present. Glauconite appears to form an important portion of upper slope "illite group" clay minerals. Montmorillonite and kaolinite decrease seaward while illite and chlorite increase. Origin of these minerals appears to be as continental detritus with long distance oceanic transport playing a role. A new parameter, the "c/k ratio" (index of relative development of the kaolinite-chlorite peaks at 3.5Å) provides an additional means of observing possible changes taking place in chlorite abundance and/or crystallinity.

INTRODUCTION

Recent studies of the clay minerals of deep sea sediments have revealed a great deal about the origin and transportation of fine sediment to its environment of deposition. Griffin and Goldberg (1963), Biscaye (1965), Berry and Johns (1966) and others have reported clay mineral distributions in the Pacific, Atlantic and North Atlantic Ocean basins respectively. With such large study areas, detailed study of relatively small areas serves to fill in some of the gaps. The samples chosen were selected because they afforded an almost linear traverse across the North Carolina Continental Margin. In this way it was hoped that any variation with distance from shore could be recognized.

ACKNOWLEDGMENTS

The writer thanks the Duke University Marine Laboratory for use of the R/V EASTWARD on cruise E-59-65 in the Cooperative Oceanographic Program. This program is supported through NSF Grant G-17669 to Duke University. Thanks are due also to S. D. Heron, Jr.,

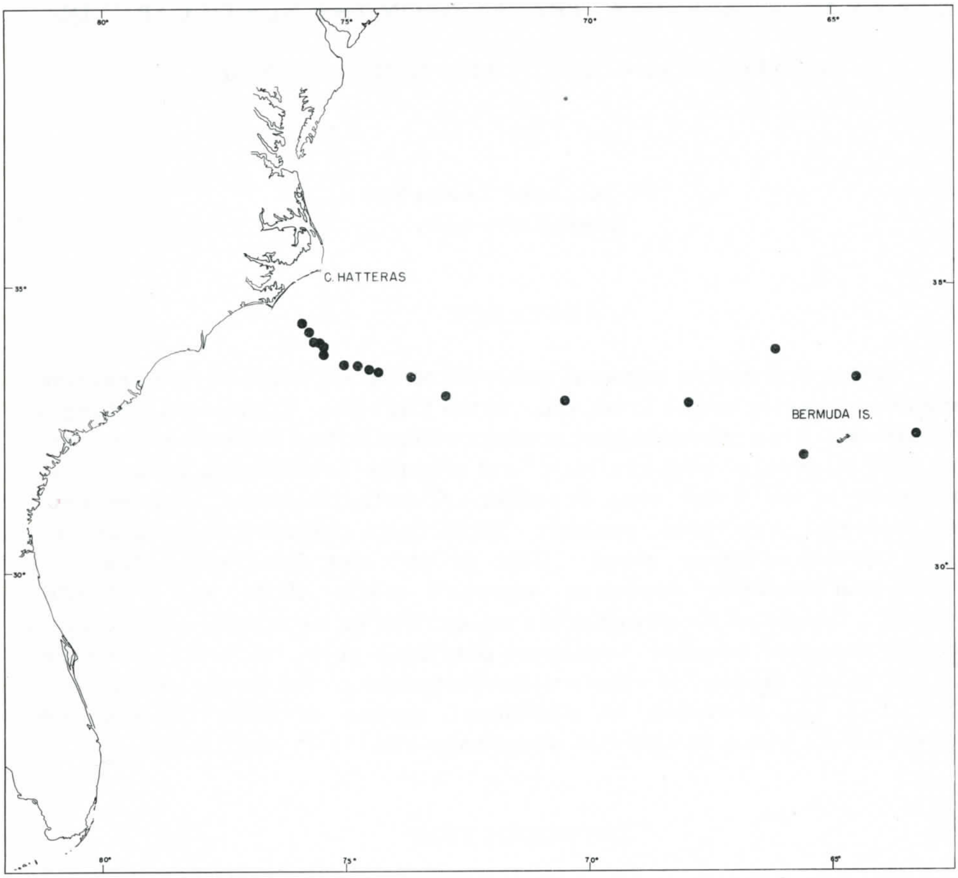

Figure 1. Index map.

O. H. Pilkey, and G. W. Lynts for advice leading to the compilation of the data herein contained. C. J. Cazeau provided additional inspiration leading to the writing of this paper. D. Pevear thoughtfully read the manuscript.

SAMPLES AND SAMPLE PROCEDURES

Eighteen gravity cores were selected for analysis of the <2 micron size fraction. The cores represent Recent sediments of the Continental Slope and Rise off North Carolina and the Bermuda Rise. The sampling pattern consists of an almost linear traverse with a series of cores ringing the Bermuda Islands (Figure 1). Table 1 gives the sediment core locations and water depth in meters. The cores are arranged in order of increasing distance from the North Carolina shore.

Table 1. Sediment core locations and water depth (meters).

Sample #	Latitude	Longitude	Depth
E 737	34°17'24" N	75°49'00" W	445
E 736	34°13'24" N	75°46'36" W	550
E 3414	34°02.5' N	75°47.0' W	1000
E 3413	34°00.5' N	75°43.0' W	1500
E 3412	33°59.0' N	75°41.5' W	2000
E 3410	33°50.0' N	75°31.7' W	3000
E 3409	33°39.0' N	75°08.0' W	3700
E 3408	33°34.5' N	74°53.5' W	3725
E 3407	33°32.0' N	74°38.0' W	4000
E 3406	33°27.8' N	74°26.0' W	4250
E 3405	33°20.0' N	73°43.0' W	4652
E 3404	33°09.0' N	73°10.5' W	5075
E 3401	33°00.0' N	70°32.0' W	5300
E 3396	33°00.5' N	68°04.0' W	5075
E 3395	33°53.0' N	66°17.0' W	4875
E 3394	33°20.0' N	64°31.5' W	4725
E 3393	32°20.0' N	63°21.5' W	4670
E 3385	32°04.0' N	65°39.0' W	4725

The calcium carbonate of each sample was removed (HCl at pH 3.5 at never more than 80°C) and the remainder of the sample processed following a standardized procedure (Heron, 1964). Ratios of peak areas of the strongest (001) reflections were compared with standard curves made of pure samples of the three main clay minerals.

Weighting factors used were: 0.73 times the area of the montmorillonite (001) peak; 3.77 times the area of the illite peak; 1 times the area of the kaolinite-chlorite peak at 7Å (001 K, 002 C); and the quartz peak area at 4.26Å was taken as a measure of abundance of quartz.

MINERAL IDENTIFICATION

Principle minerals observed in this study include: the montmorillonite group, kaolinite, chlorite, and illite (actually the term clay-mica might be preferred as finely divided muscovite, biotite and especially glauconite may be included). Other minerals observed in the clay size fraction were feldspar, quartz and mixed layer material.

Montmorillonite

Material which expands to about 17Å (001) upon glycolation is assigned to the montmorillonite group. Because measurement of the peak area of montmorillonite is imprecise due to difficulty of drawing a base line, Biscaye (1965) devised an additional measure of crystallinity (v/p ratio) which was found to be a useful parameter. Beside values for the percentage of montmorillonite present, the "v/p ratio" was also calculated.

Kaolinite and Chlorite

It is difficult to distinguish between amounts of kaolinite and chlorite by X-ray diffraction because of the similar d spacings of kaolinite (001) and chlorite (002) at 7Å, and the kaolinite (002) and chlorite (004) at 3.5Å. Various techniques, usually chemical or thermal treatment, have served to distinguish kaolinite and chlorite. Nelson (1960), Zen (1959), and others have discussed difficulties in these methods. In this study the method of Biscaye (1964) was adopted and slightly modified.

Another parameter, the "c/k ratio", was devised (Figure 2). This chlorite index measures the relative vertical development of the kaolinite-chlorite peaks and gives an idea of the relative abundance of each. It also involves the (002) of kaolinite and the (004) of chlorite and requires a scan speed of 1/4° per minute. The c/k ratio is useful because it is independent of ideal areas under the peaks and yet gives an idea of the crystallinity and relative abundance of kaolinite and chlorite.

Illite

The basal sequence 10, 5, 3.3Å not affected by glycolation is considered to belong to the illite group. The 10Å peak was used as a measure of abundance. Because the illite group was ubiquitous in the sediment studied, it seems necessary to mention another mineral with similar structure, notably glauconite.

Illite and glauconite share the same d spacings and it is difficult to ascertain the relative contribution of each. For this reason, relatively pure component slides of illite and glauconite were made in known mixtures and X-rayed to ascertain the effect of the different mixtures on each other. Slides of 100 percent illite and 100 percent glauconite and mixtures of 75, 50, and 25 percent of each were made. Comparison of the 10Å/5Å area ratios of the different mixtures indicated that with increased glauconite the peaks at both 10Å and 5Å are both reduced in size (the 5Å peak to a greater extent) although there is 100 percent of illite group present. It can be inferred then that the presence of glauconite serves to damp the illite peak and give a small diffraction tracing rather than buoying it up. As a consequence the upper slope cores,

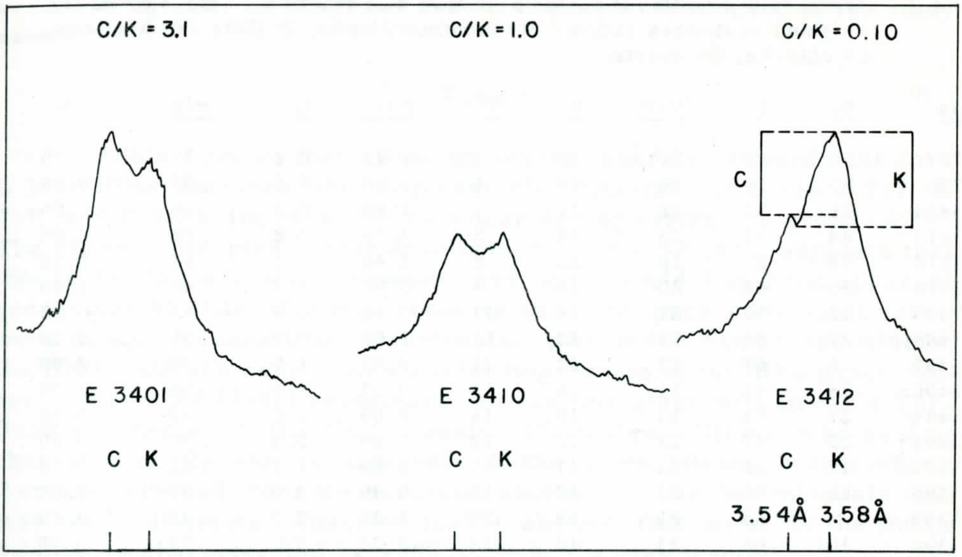

Figure 2. Typical kaolinite-chlorite doublet at 3.5Å, c/k ratio illustrated for three cores, scan speed 1/4° per minute.

which produced slides green in color, had a relatively weak (002) reflection at 5Å, and whose (060) reflection occurred at 1.51-1.52Å (Warshaw and Roy, 1961), were termed glauconitic although they produced low reflections at 10Å.

Quartz

The presence of two well defined peaks at 3.34Å and 4.26Å were attributed to quartz. Quartz in this finely divided state has been recognized in the deep sea by other authors (Biscaye, 1965; Berry and Johns, 1966; Griffen and Goldberg, 1963). The 4.26Å peak was taken to be a measure of abundance because it is not obscured by other peaks and does not appear to be affected by varying quantities of other clay size material.

Feldspar

Feldspar, as defined by two peaks in the range 3.25-3.18Å, was found to be present in every sample but no attempt was made to obtain compositional or abundance information on this material.

Mixed-Layer Material

Mixed-layer clay assemblages are common in the 10Å-24Å area. Most seems to be illite-chlorite and montmorillonite-chlorite. No attempt was made to quantify mixed-layer presence.

Table 2. Summary of results of analysis of clay-size fraction. Values given are weighted-peak-area ratios. M= montmorillonite, I= illite, K= kaolinite, C= chlorite, Q= quartz.

Core	M	I	K+C	K	C	K/C	Q	v/p	c/k
E 737	58	18	24	17	7	2.23	0.2	.75	0.05
E 736	60	16	24	18	6	3.00	0.6	.80	0.05
E 3414	36	32	32	21	9	1.90	0.3	.60	0.05
E 3413	44	33	23	18	5	4.00	0.2	.72	0.05
E 3412	45	27	28	20	8	2.40	0.3	.62	0.10
E 3410	35	44	20	16	4	0.92	0.7	.49	1.00
E 3409	22	50	27	14	13	1.10	0.9	.53	0.55
E 3408	21	54	24	12	12	1.00	0.9	.51	3.30
E 3407	6	67	27	12	15	0.85	1.0	.39	2.00
E 3406	25	53	21	6	15	0.37	1.0	.55	4.30
E 3405	21	55	23	10	14	0.69	1.0	.39	3.80
E 3404	20	57	22	10	12	0.80	0.9	.30	0.60
E 3401	17	58	24	11	13	0.80	1.2	.42	3.10
E 3396	26	50	22	10	12	0.88	2.0	.60	1.00
E 3395	4	64	29	16	13	1.20	3.3	.43	4.70
E 3394	10	66	23	10	13	0.76	Tr	.33	3.50
E 3393	6	70	24	10	14	0.67	0.6	.31	2.44
E 3385	1	76	23	11	12	1.00	0.6	.35	1.00

RESULTS

The results of this study are summarized in Table 2.

Montmorillonite

A general decrease in montmorillonite abundance occurs seaward (Table 2) and is especially marked on the continental margin. Biscaye (1965) mentions that montmorillonite, of all the clay minerals, is most likely to have a composite origin (detritus from continents and volcanic alteration material). Volcanism is conspicuously absent in the Southeastern United States, but to the south the Carribbean area is the site of Recent volcanic activity.

Biscaye (1965) does not agree with Griffin and Goldberg's (1963) idea that what is commonly called montmorillonite from continental sources is really stripped illite and chlorite. In a sequence of samples across the North Pacific, Griffin and Goldberg (1963) observed a decrease of 17Å expandable material and crystallinity with a simultaneous increase in the amount of illite and chlorite. These stripped clay minerals would fix more K and Mg ions and convert to unexpanded or normal illite and chlorite with increasing distance from shore and thus a longer exposure time to the marine environment. The effect would then appear as a seaward decrease in montmorillonite. Biscaye (1965) found that in no sequence of cores studied (500 Atlantic cores) did the montmorillonite abundance or the "v/p ratio" decrease. The results of this investigation indicate that montmorillonite abundance as well as the crystallinity ratio do decrease seaward to a marked degree in the study area.

Illite

Table 2 shows that illite increases sharply seaward. At core E 3410 illite becomes the dominant clay mineral. In cores E 737, E 735, and E 3414 the clay fraction upon drying assumes a green color. The green color plus a poor development of the 5Å (002) suggests that this is due to glauconite presence and thus would lower the apparent percentage of illite if comparison to an illite pure component curve were made. As mentioned previously, glauconite damps and widens the illite peak and hence gives a false impression of the illite group present. Wermund (1961) recognized clay-sized glauconite in early Tertiary sediments of the Gulf Coastal Plain also. Illite can be said to characterize Recent clay minerals in the North Atlantic basins where they are removed from any proximal source of other clay minerals that may act as dilutants. Biscaye (1965) showed that most of the North Atlantic is characterized by >50% illite in the clay fraction.

Kaolinite-Chlorite

The presence of kaolinite and chlorite, as indicated by the area of the peak at 7Å (001 K, 002 C), maintains a relatively constant percentage over the study area (Table 2). With resolution of the kaolinite-chlorite doublet at 3.58-3.54Å slight variations become apparent. Kaolinite decreases slightly seaward while chlorite increases slightly. The change becomes more apparent when the ratio of area under the resolved doublet is considered. Continental slope clays show a sizable decrease in the K/C values.

The c/k ratio (chlorite index) shows a dynamic change that may be meaningful here. The c/k ratio computed for the peaks at 3.58-3.54Å seems to be a more sensitive measure than the previously mentioned parameters (Table 2). In cores E 3412 to E 3410 the change is from a low index to a relatively high one. This change occurs at 2000-3000 meters and probably represents a change in chlorite abundance as well as crystallinity as defined by a better development of the chlorite (004) peak at 3.54Å. In addition, the c/k ratio change was accompanied by a stronger development of the (001) of chlorite at 14.2Å and coincides with the slight 4-5 percent increase in abundance of chlorite.

Quartz

Quartz is present in amounts ranging from a trace to 3 percent. It increases to a maximum in cores E 3396 and E 3395, which are both located on a portion of the Bermuda Rise, in an area in which pelagic sedimentation is important (Heezen and Laughton, 1963). The presence of burrow mottling in these cores tends to confirm their pelagic origin.

Eolian transport of clay size quartz particles was noted by Arrhenius (1963, Figure 25). Quartz of 1 micron size was found to be an important constituent of pelagic sediments. His diagram of the tropospheric transport of dust indicates that there is at least a small amount of eolian quartz available to the present study area.

DISCUSSION

The presence of montmorillonite on the upper slope and its decrease seaward can be explained in several ways: (1) the montmorillonite is of continental origin and simply decreases in abundance with increasing distance from the continent and hence source: (2) montmorillonite is the alteration product of another clay mineral, dioctahedral vermiculite, and decreases as (1) above; (3) transport from another source such as the Caribbean area or the Gulf of Mexico; (4) the montmorillonite decrease is an apparent one with stripped illite and chlorite becoming regraded (Griffin and Goldberg, 1963).

Montmorillonite is present in the marine sediments of the Coastal Plain of the Southeastern United States (Heron et al, 1964). The rivers of the Southeast are carrying very little or no montmorillonite and are rich in kaolinite and dioctahedral vermiculite. Heron et al (1965) found that upon entering the estuarine environments of the Southeastern United States dioctahedral vermiculite disappeared and montmorillonite became more abundant. The simularity of the two 14Å minerals leads to the possible alteration of dioctahedral vermiculite to montmorillonite.

Since the Caribbean area is one of volcanic activity, oceanic currents such as the Florida Current could transport some montmorillonitic material from the Caribbean or the Gulf of Mexico, but interchange of suspended material from the Gulf to the Florida Straits is minimal (Griffin, 1962). Furthermore, the Florida Current is carrying small amounts of suspended sediment.

The regrading of illite and chlorite in the marine environment (Griffin and Goldberg, 1963) with increasing distance from source does not appear important in the study area. The rivers of the Southeastern United States are carrying a barely detectable amount of illite and no chlorite (Nelson, 1960, and Heron et al, 1964). Hence, it seems unlikely that a regrading mechanism is important in the study area. If it does occur, its effect would be difficult to detect and probably minimal.

Illite is ubiquitous in the Recent clay mineral assemblage of the North Atlantic Ocean. Upper slope sediments yield low illite values while the clays appear to contain glauconite. Perhaps this is due to the damping effect of the glauconite. The illite abundance rises sharply on the Continental Slope and Rise and increases seaward to values of over 50-60%. This increase reflects a decrease in the amount of dilution by other clay minerals and, in the case of the upper slope, glauconite. K/Ar ages of illites in the Atlantic (Hurley, et al, 1963) point to a continental source because ages in the neighborhood of 80-200 million years are cited. Illite increase seaward could then be attributed to less dilution from continental sources and perhaps transportation by oceanic currents from other areas.

The relatively low values of chlorite and their increase seaward point to the sea as the source. Perhaps the increase in chlorite reflects transportation by oceanic currents from areas of high chlorite abundance to the north (Biscaye, 1965).

The decrease of kaolinite seaward suggests a continental origin. The soils of the Southeastern United States are particularly rich in kaolinite, and the rivers carry a great deal of kaolinite in suspension. The kaolinite that escapes flocculation in the estuaries is probably carried seaward and decreases in abundance with distance from shore.

The increase in quartz concentration to a high on the Bermuda Rise results from the increasing importance of eolian contribution in an area of pelagic sedimentation. Since pelagic areas have low sedimentation rates, it appears likely that quartz contributed by eolian mechanisms assumes relative importance with a decrease in influence of a proximate source for terrigenous, water-borne materials.

SUMMARY

Montmorillonite decreases markedly seaward while illite increases in Recent sediments of the North Carolina Continental Margin. Kaolinite and chlorite taken as a whole do not vary greatly, but with resolution a slight pattern emerges with kaolinite decreasing and chlorite increasing seaward. The chlorite index (c/k ratio) points to a change either in abundance and/or crystallinity not apparent in the percent abundance parameters. Glauconite forms an appreciable amount of 10Å illite group clay minerals on the upper slope. Quartz, probably contributed by eolian mechanisms, is highest in an area of slow sedimentation.

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DENSITY SORTING AS INDICATED BY DEPARTURE FROM GAUSSIAN CURVE

by

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ABSTRACT

There is a direct correlation between heavy mineral concentration, Ø size, and slope break. This correlation will be indicated as a departure from the Gaussian, an increase in slope, where there is more than approximately 2% heavy mineral content in any one sand size fraction. Such a departure from the Gaussian may be attributed to density sorting.

INTRODUCTION

The basic concept that a size frequency distribution will plot as a straight line on probability paper is assumed to be correct. It is proposed that a detailed examination of the physical factors controlling sedimentation may provide an explanation for certain distributions which are not Gaussian. Specifically, it is thought that density sorting is a cause of some of the deviations seen in polymodal distributions.

Acknowledgments

I wish to express my appreciation to Robert E. Stevenson, who proposed this study and to H. G. Goodell and W. F. Tanner, whose guidance was received throughout the preparation of this paper.

METHODS OF STUDY

Examination of 70 sediment samples provides the data for this paper. All of the samples are from a brook near Larkins' Bluff (Figure 1) located about 40 km west of Tallahassee, an excellent natural laboratory for stream and sediment study. At the Bluff a small amphitheater has been carved out of unconsolidated sand by gully-wash and slumping. Spring flow from the amphitheater has moved slumped sand out onto a fan complex. The whole system is but 100 meters in length, and 15-20 meters at the widest point at the base of the fan.

Two 1964 hurricanes affected the tests: Dora and Hilda. Dora approached Larkins' Bluff about 0800 hours September 10th. The most

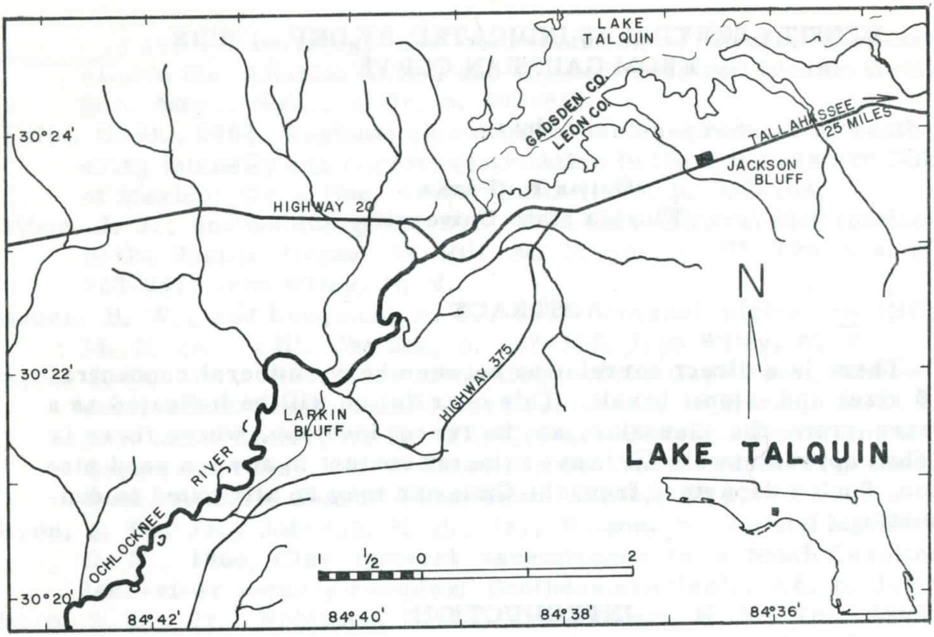

Figure 1. Location of Larkins' Bluff.

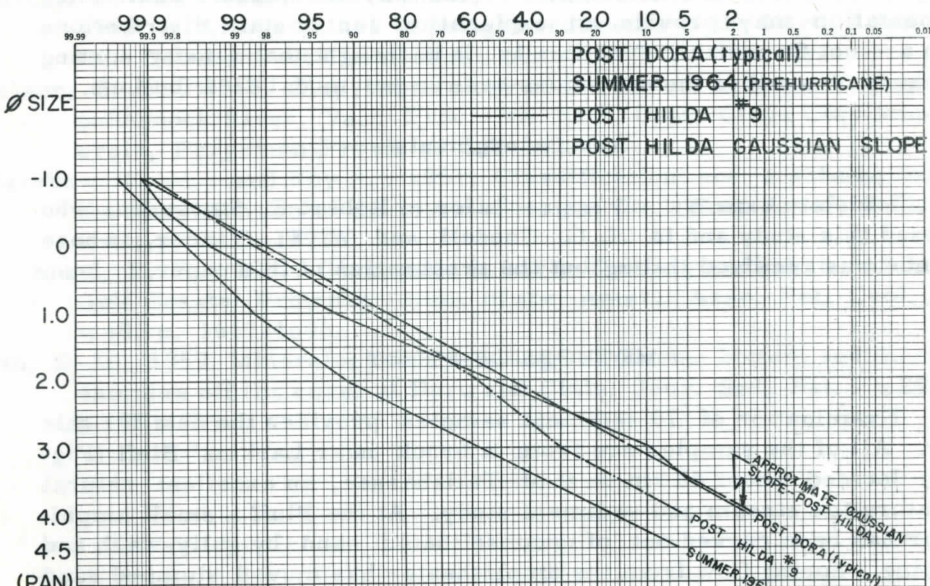

Figure 2. Additional sieving time would probably increase the break in the post-Dora curve in sizes from Ø to Ø 4.5.

intense rain fell in a five hour period beginning at 2000 hours, totalling 3.145 inches. Hilda passed the area on Ocotber 1st; during a 45 minute interval 1.5 inches of rain fell in the general area. The total rainfall for each storm was approximately 14 inches.

The rains caused drastic changes in the erosional and depositional features of Larkins' Bluff. The stream channel shifted radically and entrenched itself into the underlying clay, which is the confining material for the local perched ground water table. Further, the fan shifted down stream some fifty meters.

Sediments samples were taken at three intervals: pre-hurricane (summer 1964), post-Dora and post-Hilda. Samples were taken within three days after the storm passage. There were 10 pre-hurricane, 40 post-Dora and 20 post-Hilda samples. These were collected from several lines across the stream channel and the fan.

Normal procedures were used for the sieving of all samples; however, sieving time was not constant. Fifty of the samples were sieved for an average of 15 minutes (pre-hurricane and post-Dora), and twenty post-Hilda samples were sieved in accordance with the findings of Mizutani (1963). Consequently, the sieving time was approximately doubled for the post-Hilda samples. All data were obtained using 1/2 ϕ sieves.

RESULTS OF STUDY

The post-Dora sieving results, plotted on probability paper, had consistent breaks at 3 ϕ, noted on every plot of the 40 samples (Figure 2). The post-Hilda plots were, for the most part, Gaussian (Figure 3). The exceptions in these post-Hilda plots were those samples which had heavy mineral concentrations of over 2 percent. Some were unusually heavy concentrations. For example, sample #3 had 3.49 percent of heavy minerals and sample #9 had 17.83 percent. There was no heavy mineral detected larger than 3 ϕ except in sample #9, post-Hilda.

There was no distinct slope break in any of the post-Hilda plots at other than 3 ϕ except in sample #9. Where the heavy minerals were concentrated largely in the pan the slope was Gaussian, or very nearly so (Figure 3).

There was no significant difference between the sorting of the post-Dora and the post-Hilda plots. The average coefficient of sorting (So value) was 1.38, a well sorted sediment according to Trask (1932). Pre-hurricane sands were finer by about 1 ϕ unit than the post-hurricane samples.

Bromoform was used to separate the heavy minerals. Samples 3 and 9 (post-Hilda) represent cases of those samples containing concentrations of heavy minerals (Table 1).

After identification of the heavy minerals the hydraulic equivalents were computed using Rittenhouse's data (1943). Results were as

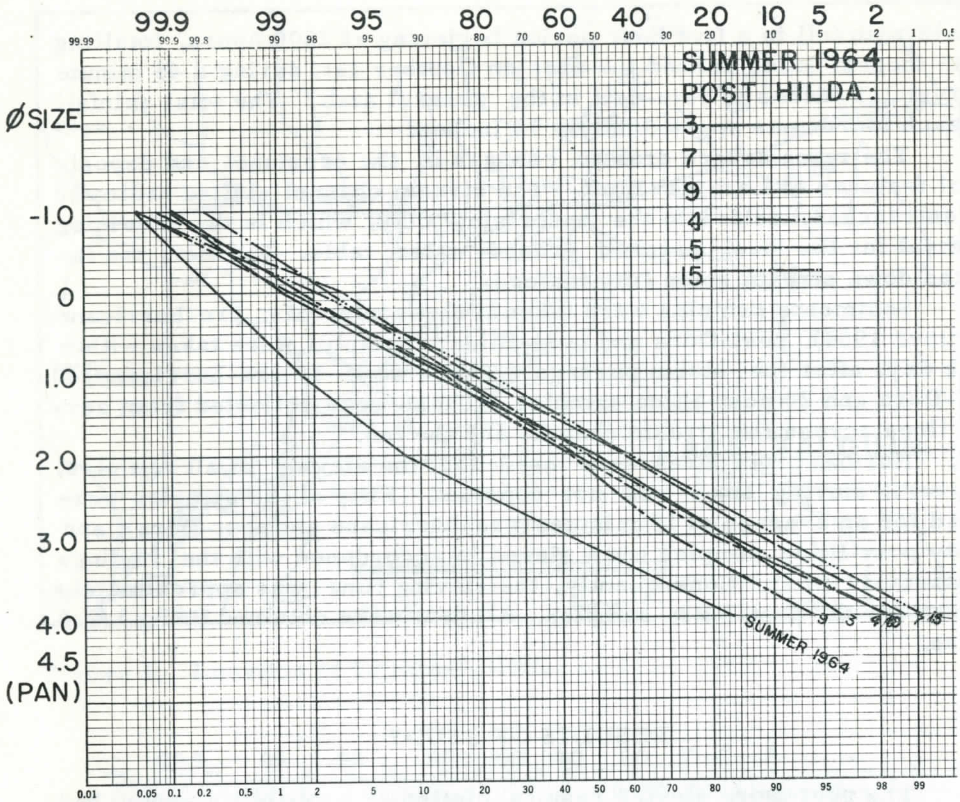

Figure 3. There was no distinct break in any of the post-Hilda plots at other than 3 Ø except in sample #9. Heavy minerals indicated by break and departure from Gaussian, i. e., sample #3 and #9.

noted in Table 2.

The average hydraulic factor for the heavy mineral suite was computed to be 0. 7. If one-half this factor, 0. 35 of a Ø size, is applied to the slope below the break, for example, sample 9 at 3 Ø, such manipulation will tend to restore the Gaussian curve (Table 2).

CONCLUSIONS

It is concluded that the break in slopes found during this series of tests is directly related to density sorting. In considering other factors or agents, the short sieving time, for example, must be discounted as a factor in explaining the slope break. Any increase of sieving time for prehurricane and post-Dora samples would emphasize the breaks (Mizutani, 1963) (Figure 4). No screen damage was found

Table 1. --Heavy Mineral Content of Sands at Larkins' Bluff

Sample #3
(Total Weight of Sample 101. 240 grs.)*
No heavy minerals in sizes Ø-1 through Ø-2. 5

Ø Size	Grams of Ø Size		% of Heavy Mineral Per Ø Size in the Total Sample
3	31. 830		0. 201
4	14. 705		1. 192
4. 5	9. 900		2. 103
		TOTAL	% = 3. 496

Sample #9
(Total Weight of Sample 100. 10 grs.)*
No heavy minerals in sizes Ø-1 through Ø-1. 5

Ø Size	Grams of Ø Size		% of Heavy Mineral Per Ø Size in the Total Sample
2	29. 14		1. 000
3	28. 236		4. 567
4	24. 308		9. 871
4. 5	6. 310		2. 495
		TOTAL	% = 17. 833

*Sample weights are taken prior to sieving, during the process #3 lost . 878 grs. while #9 lost . 612 grs. The fact that each sample has a total weight of approximately 100 grs. allows weights of individual Ø sizes to be used as percentages.

in a careful examination of all the screens used.

There has been shown, however, to be a direct correlation between heavy mineral concentration, Ø size, and slope break. Though empirical, the application of the fraction of the hydraulic equivalent to that portion of the slope below the break does restore the Gaussian curve for the various samples used in these tests.

The Gaussian distribution will be found where there is sufficient range in particle sizes, sufficient quantity, where sediments are controlled predominantly by one transporting agent, where the sand is monomineralic and where there is a single source area.

Table 2.--Heavy Minerals and Their Hydraulic Equivalents

Determined Using Rittenhouse's Data (1943)

Minerals	Percentage	Hydraulic Factor
Ilmenite, Magnetite, and Leucoxene[1]	20.0	1.0
Monazite	10.0	1.0
Zircon	20.0	.9
Garnet, Epidote, Chert, and Hornblende[2]	7.5	.6[2]
Staurolite	10.0	.4
Rutile	2.5	.7
Tourmaline	15.0	.2
Kyanite	15.0	.3
	Average Hydraulic Factor is	.7

1. These minerals were grouped as they were relatively low percentage (5%-8%) of total sample and had similar hydraulic factors.
2. These minerals were grouped as they were relatively low percentage (1%-4%) of total sample and all had similar hydraulic factors.

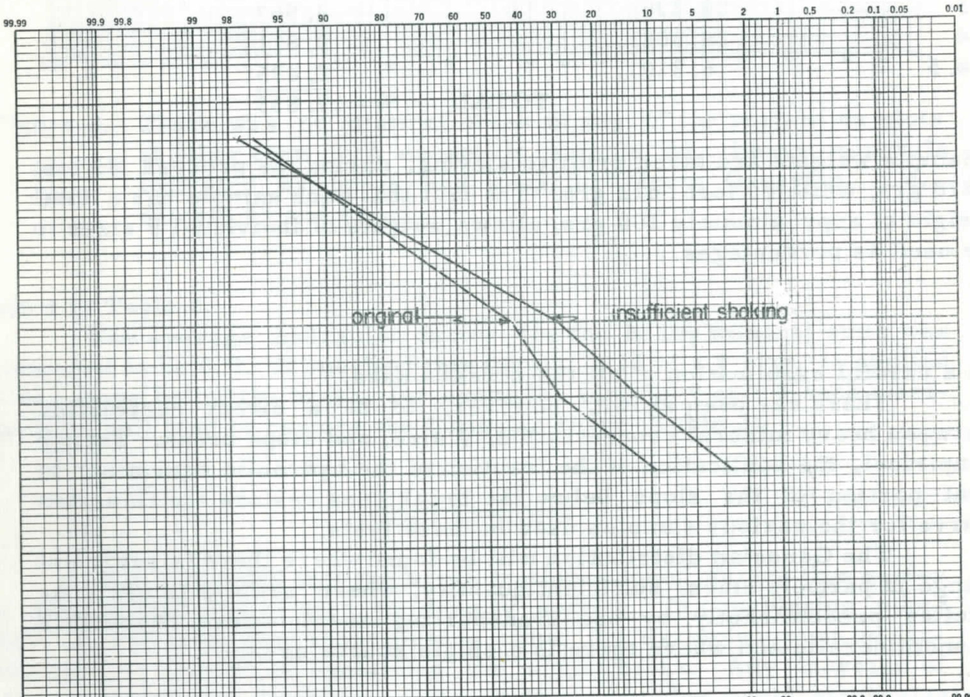

Figure 4. Additional sieving time tends to increase the departure of the curve from the Gaussian. From Mizutani, 1963, p. 24.

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COASTAL PLAIN STRATIGRAPHY AND GEOMORPHOLOGY

NEAR BENSON, NORTH CAROLINA [1/]

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ABSTRACT

The "high-level" sediments in the Benson, North Carolina, area may be divided into the Macks Formation, newly differentiated, Pinehurst Formation, and a "Brandywine Formation." The Macks Formation is upper Miocene. The Macks is a silty, very fine sand that is relatively uniform. It is overlain by the medium to coarse sands plus clay tentatively correlated with the Pinehurst Formation of probable Pliocene age. The "Brandywine Formation" is stratigraphically above the Pinehurst. The erosion surface at the base of the "Brandywine" truncates both the Macks and Pinehurst Formations.

This erosion surface is not everywhere buried by the "Brandywine Formation" and its subaerial portion is mapped as Coats scarp. This scarp is believed to be, in part, correlative with the Orangeburg scarp in South Carolina which is regarded as a mid-Miocene sea cliff. But, the Coats scarp of North Carolina is a Pliocene or Pleistocene feature.

1/ Joint contribution from the Soil Conservation Service, USDA, and the Soil Science Department, North Carolina Agricultural Experiment Station, Raleigh, North Carolina. Published with the approval of the Director of Research as Paper No. 2245 of the Journal Series.

INTRODUCTION

Benson, North Carolina, is in Johnston County on the Neuse - Cape Fear drainage divide (Figure 1). The surrounding area has a complex stratigraphic and geomorphic history because it lies along the boundary between the upper and lower Coastal Plain[2/] (Heron, 1958). We have mapped the sediments and geomorphic surfaces of the area in detail and reconnaissance. We can recognize stratigraphic and geomorphic changes that are similar to those in South Carolina near the Orangeburg scarp but our interpretation of the time element differs. We believe that the available information should be presented to point out both similarities and apparent anomalies that occur between North and South Carolina.

Methods

Sediments were studied in roadcuts and bore holes. In bore holes, auger flights were pulled every 5 to 10 feet to minimize disturbance of sedimentary contacts. The cross sections shown are not idealized diagrams. Each cross section of an interstream divide was constructed from bore holes no more than one mile apart. At scarps and other critical areas the bore holes, in places, were 30 feet apart. Horizontal distances were measured along divides on aerial photographs following all the sinuosities of the divide. Distances were paced or measured by stadia board at scarps and other areas where bore holes were closely spaced. Altitudes were determined by level. Areal mapping of sediments was done on four- and two-inch-per-mile aerial photographs.

2/ We prefer to classify the Coastal Plain into upper, middle, and lower physiographic regions. The upper Coastal Plain extends from the Coastal Plain-Piedmont boundary eastward to the Coats scarp, or at altitudes of about 300-275 feet. The middle Coastal Plain extends eastward from this scarp to the Surry scarp, or an altitude of about 100 feet (Daniels, et al. 1966). The lower Coastal Plain is east of the Surry scarp. There are unpublished data (Soil Survey Investigations, Soil Conservation Service, U. S. Department of Agriculture) that indicate major changes in stratigraphy, geomorphology, and soils at these subdivision contacts. Part of that information is given in this report. The rest will appear in subsequent papers.

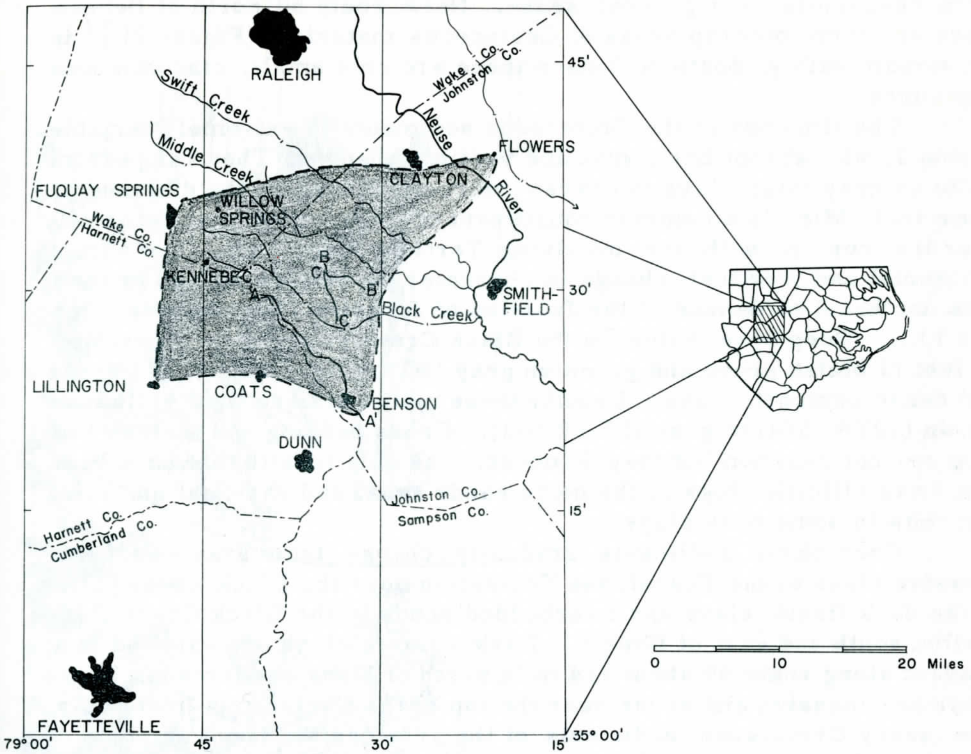


Figure 1. Location of area studied near Benson, North Carolina. Detailed and reconnaissance study areas are within the dashed line.

STRATIGRAPHY

Bedrock

The basement rocks in the area are a complex suite of mica gneisses and felsic volcanics of Precambrian age (Stuckey, 1958). Occasional outcrops are found in the Black Creek valley (Figure 1) at and below North Carolina route 50. Upstream in this valley, bedrock outcrops become more common, for example, near the junction of route 210 and Black Creek. The bedrock, where exposed, usually has been weathered to a soft saprolite.

Cretaceous Formations

The basal unconsolidated deposit in the area is either the Tuscaloosa or the Black Creek Formation (Pusey, 1960). We are using the term Tuscaloosa in a general sense. Near route 50 north of Benson there are large outcrop areas of Cretaceous materials (Figure 2) 3/ in the stream valley. South of Benson there are only small, discontinuous exposures.

The lithology of the Cretaceous sediments is extremely variable (Table 1) with abrupt horizontal and vertical changes. They range from white or gray tough clays to coarse micaceous sands in the distance of a few feet. Mica is a common constituent of these materials, especially near the contact with the overlying Tertiary sediments. The abrupt horizontal and vertical change in character is well expressed in road cuts northeast of Benson at the Junction of Johnston County roads 1365 and 1321. Deep bore holes in the Black Creek valley have penetrated 30 feet of bluish green and greenish gray (5GY 5/1 to 5BG 7/1 4/) sands and dense compact clays. Usually these materials are light yellowish brown (10YR 6/4) to gray (10 YR 5/1). Cross bedding and festoon bedding are not common but they do occur. The only fossils that have been found are silicified logs in the more sandy areas and rare leaf and stem imprints in some dark clays.

Cretaceous sediments gradually change from gray sands and massive clays of the Tuscaloosa Formation near the Black Creek valley to the dark fissile clays and interbedded sands of the Black Creek Formation south and east of Benson. Dark colored clays are exposed in a roadcut along route 50 about 1/4 mile north of Mack crossroads. These clays are massive and occur near the top of the Cretaceous materials. The sandy Cretaceous sediments of the area contain large amounts of montmorillonite (Craig, 1963 and Cady) 5/. Along Johnston County road No. 1321 black, fossiliferous (plant remains) fissile clays are exposed about 1/4 mile south of the junction of roads 1321 and 1168. These clays overlie sediments more typical of the Tuscaloosa. South of Benson on route 50 at the Banner Church, black fissile clays typical of the Black Creek are exposed. But sediments typical of the Tuscaloosa are found in bore holes in the area about as often as sediments of the Black Creek.

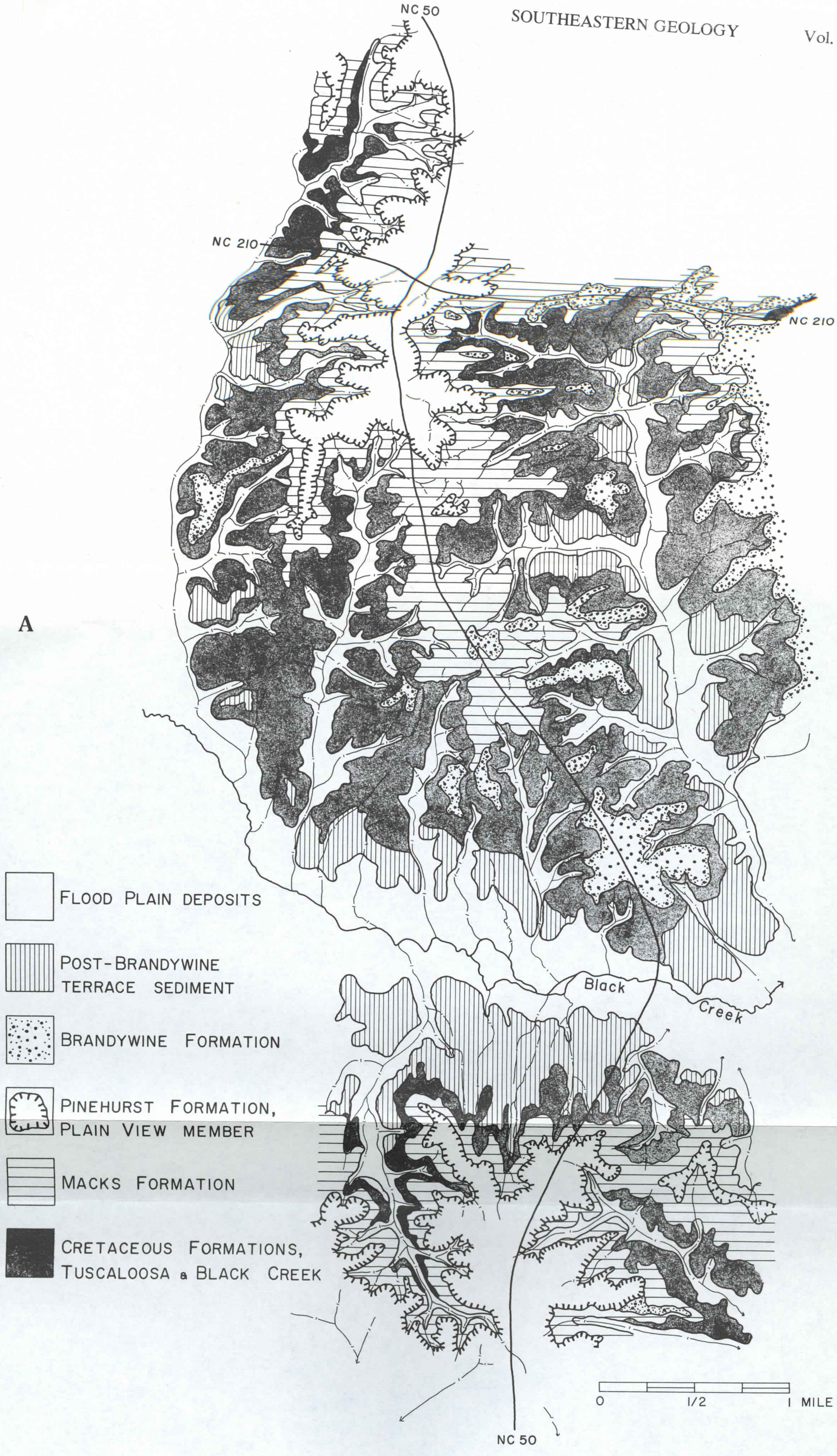
In places, sediments with the lithology of the Black Creek Formation may overlie sediments with the lithology of the Tuscaloosa. But there also are areas where the sediments are gradational, both mineralogically and lithologically. Our experience is that a sharp line does

3/ Most outcrops of Cretaceous and Tertiary materials shown in Figure 2 have a covering of 1 to 5 feet of post-Brandywine sediments. These sediments are thickest in the concave cove areas and thinnest on the convex spur ridges. Their characteristics are strongly influenced by the character of sediments higher on the slope.

4/ Munsel soil color of moist sediment.

5/ Cady, J. G., Unpublished data, Soil Survey Laboratory, Soil Conservation Service, Beltsville, Maryland.

A



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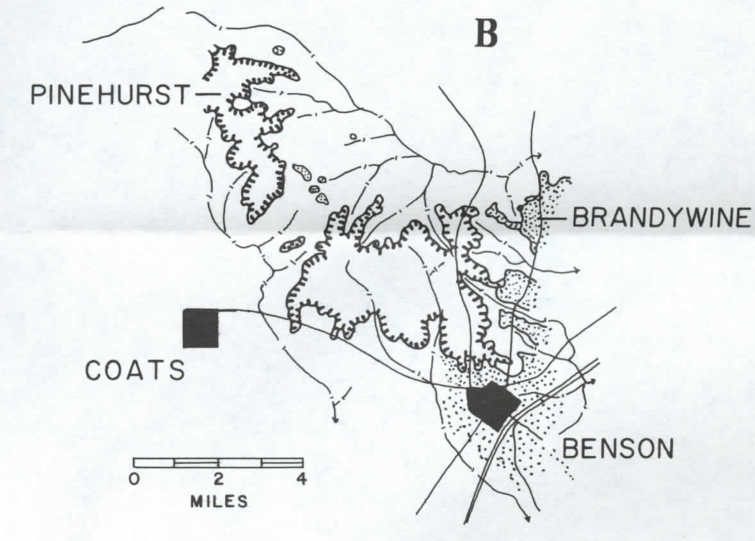

Figure 2.

A. Outcrop areas of Cretaceous, Macks, and Pinehurst Formations in the Black Creek valley north of Benson.

B. Outcrop areas of the Pinehurst Formation and "Brandywine Formation" on the Neuse-Cape Fear Divide near Benson.

Table 1. Silt, clay, dominant sand fraction, and roundness of sediments near Benson, North Carolina.

Formation	Silt Average percent	Silt Range	Clay Average percent	Clay Range	Dominant Sand Fraction (mm) (percent of samples) 2-1	1-.5	.5-.25	.25-.125	.125-.062	Roundness a/ (.5 - .25 mm) average	range
Brandywine	6.1	1.1 30.7	12.4	4.0 25.0	19	62	5	14		.312	.301 - .334
Pinehurst	7.4	1.8 19.9	14.0	6.3 22.7		57	38	5		.333	.305 - .348
Macks	20.5	12.4 42.8	15.6	6.7 29.9			4	27	69	.325	.298 - .334
Tuscaloosa	18.2	6.8 36.5	24.6	11.0 67.8		13		63	24	.314	.303 - .342

a/ Roundness determined by the method of Powers (1953).

not separate these formations and they should be considered to have a gradational contact (See Heron, 1960).

Macks Formation

General Features. The Macks Formation is a newly distinguished unit that previous workers probably have included within the Cretaceous. It crops out on valley slopes in the Black Creek valley and elsewhere (Figure 2), but it is overlain by surficial sediments on interstream divides. It seldom crops out on a divide except in small areas on the scarp separating the Pinehurst and "Brandywine" Formations (Figure 3).

The Macks has a distinctive lithology that makes it easy to separate from other formations. The upper part usually is a massive, micaceous, fine to very fine sandy loam to sandy clay loam[6/]. But, there are small areas of clay to very fine sandy clay exposed along Johnston County road 1331 north of Benson. The upper micaceous materials change downward gradually, locally abruptly, to a less micaceous, usually some what coarser sediment. Rounded to well rounded quartz pebbles occur at the base, and most have a rough surface. The contact to the Cretaceous formations is sharp and has a local relief of 5 feet or less.

Silt content of the Macks is uniformly above 10 percent, and most of the sand is in the very fine sand fraction (Table 1). Near Benson pebbles at the base of Macks are discoidal, rough surfaced, and well rounded. These discoidal gravels are well shown north of Benson at the junction of Johnston County roads 1331 and 1168. They are al-

6/ Textural classes based on USDA soil textural triangle (Soil Survey Staff, 1951, p. 209).

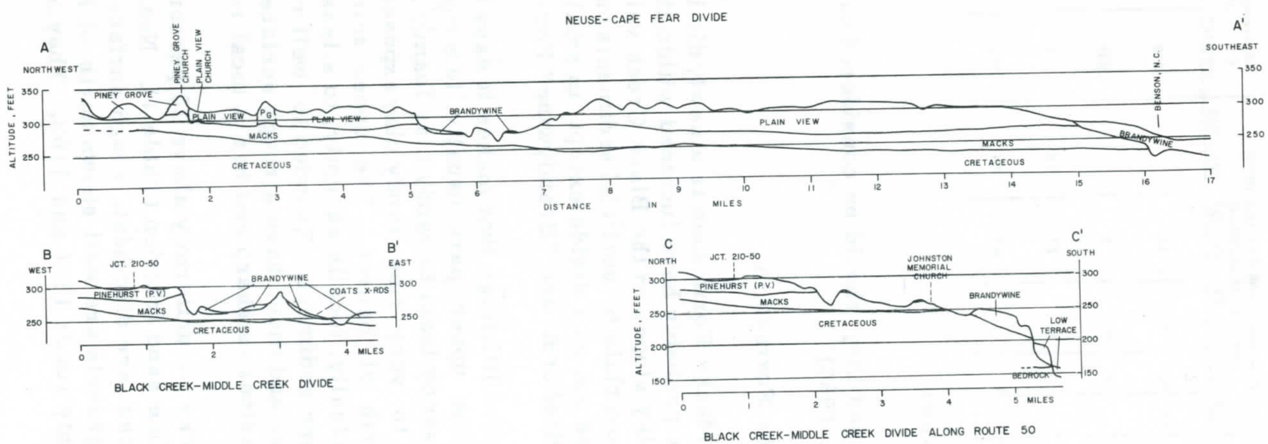

Figure 3. A-A' Sediments on the Neuse-Cape Fear divide from a point one mile south of route 210 to a point south of Benson, North Carolina;
B-B' Sediments on the Middle Creek-Black Creek divide;
C-C' Sediments from the Middle Creek-Black Creek divide to the Black Creek valley. The "Brandywine formation" caps the divide just north of Johnston Memorial Church.

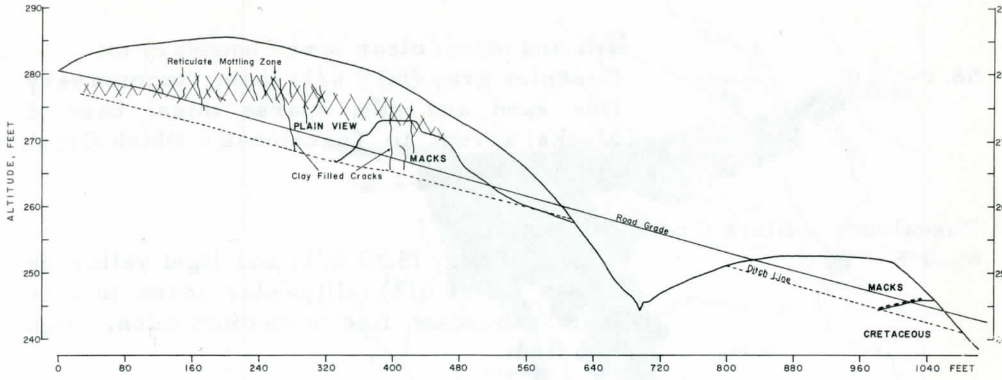

Figure 4. Sequence of sediments at a section on the west side of N. C. highway 50 about 1/8 mile north of the junction of Johnston County road no. 1308 and highway 50.

most duplicates of the beach gravels that Stephenson (1912) found in his Coharie Formation near this area. The Coharie as defined by Stephenson lies east of the Macks and overlies an erosion surface that has cut through the Macks into the underlying sediments. Some of the discoidal gravels in the Coharie may be from the Macks.

The best place to see a typical outcrop of Macks is about 1/8 mile north of Macks crossroads on N. C. highway 50 north of Benson. Macks crossroads is 5 miles north of Benson. Here the nature of the contact to the overlying sediments is easily seen, the formation has its distinctive lithology, and its relation to the underlying Cretaceous sediments can be examined (Figure 4). The type section of Macks is a bore hole 0.3 mile north of the junction of route 50 and Johnston County road no. 1168 and 0.1 mile east of N. C. highway 50, Johnston County, North Carolina.

Depth, feet	Description of Type Section
Pinehurst Formation 0-33.5	A mixture of sand and clay with an abrupt lower boundary.
Macks Formation 33.5-41.0	Variegated yellow (10YR 5/6) and light red (2.5YR 6/6) loam; abundant very fine sand, silt, and fine mica; gradual lower boundary to:
41.0-52.0	Yellow (10YR 7/6) fine sandy loam to loam; common light red (2.5YR 6/8) mottles; abundant silt and mica; gradual lower boundary to:
52.0-58.0	Yellow (10YR 7/8) fine sandy loam to loam; common white (2.5Y 8/2) mottles; common

	silt and mica; clear lower boundary to:
58.0-65.0	Greenish gray (5GY 6/1) loam; common very fine sand and silt; sparse mica; base of Macks; abrupt to Tuscaloosa - Black Creek Formation.
Tuscaloosa - Black Creek Formation	
65.0 +	Greenish gray (5BG 6/1) and light yellowish brown (2.5Y 6/4) silty clay loam to clay loam; abundant fine to medium mica; tough and firm.

Areal Distribution. The areal distribution of the Macks is not fully known. We have not identified it southwest of Coats or northeast of Flowers on Route 42 east of Garner (Figure 5). Farther south and west of Coats and northeast of Flowers, the Macks disappears and overlying sediments rest on bedrock. The most northwestern outcrop known is at the U. S. 401 - railroad overpass east of Fuquay Springs. The detailed distribution of the formation near Benson is given in Figure 2. The eastern and southeastern boundary of the Macks is closely related to the Coats scarp (Figure 5). This scarp cuts out the overlying sediment and the Macks.

Sediments that are definitely the Yorktown Formation lie to the north and east of the Macks outcrop area. The nearest Yorktown was penetrated in a well near the Nash-Wilson County line about 13 miles from the northeast limit of the Macks. This Yorktown material is finer-grained than the Macks and contains abundant calcareous marine fossils including Yorktown forminifera (identified by Joseph St. Jean). The Macks is coarser grained and contains no calcareous fossil remains. Its relation to Yorktown (unconformity or lateral facies?) is as yet unsolved.

An outcrop area near Clayton shown on the Geologic Map of North Carolina (Stuckey 1958) is the Macks Formation rather than the Yorktown Formation.

Fossils and Age. The Macks Formation has yielded fossils at only a few localities. The only locality to yield significant numbers of identifiable fossils is a drainageway that crosses highway 50 about 0.2 mile north of the junction of route 50 and Johnston County road 1305. The Macks is exposed discontinuously in the base of the drainageway starting about 200 yards northwest from highway 50. Here moderate numbers of external molds, casts of external molds, and a few internal molds of pelecypods were found. Fortunately, these were good enough to permit identification of the fauna as being of lower Yorktown (lower part of upper Miocene) age. Two small internal molds of gastropods were observed but deemed not identifiable.

A preliminary list of fossils is:

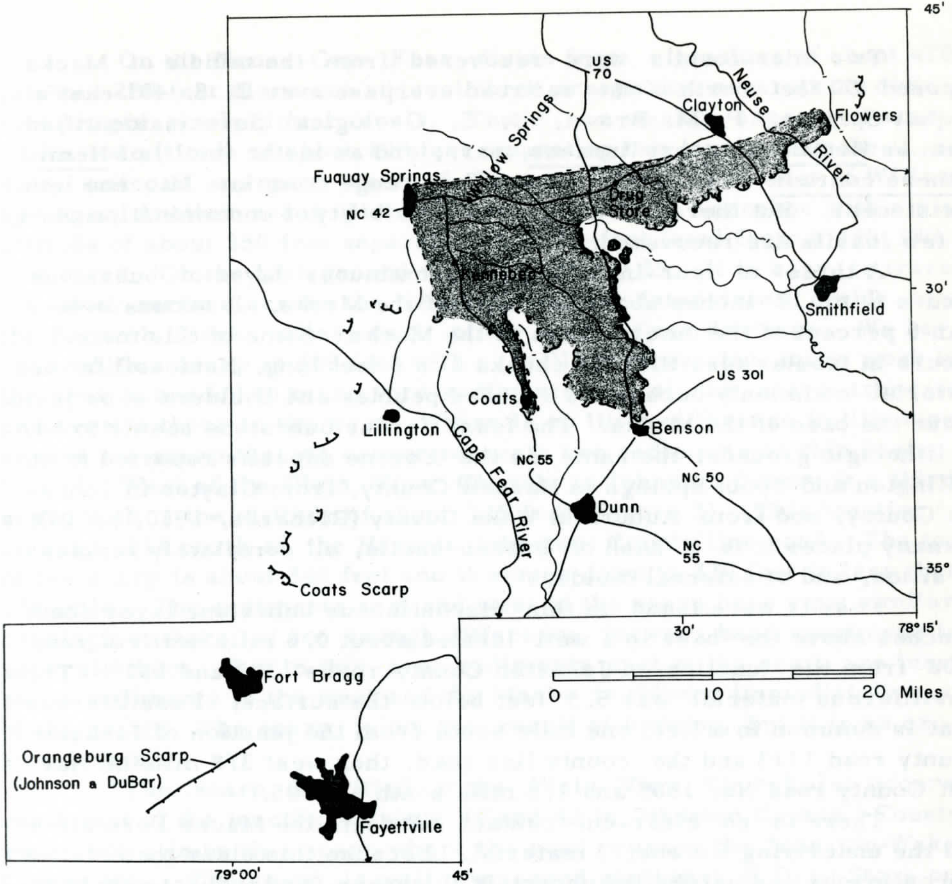

Figure 5. Generalized outcrop area of the Macks Formation.

Anadara cf. A. idonea (Conrad)
Anadara transversa (Say)
Glycymeris cf. G. subovata (Say)
Chlamys eborea (Conrad)
Chlamys decemnaria (Conrad)
Chlamys cf. C. jeffersonius (Say)
Chione latilirata (Conrad)
Mercenaria campechiensis (Gmelin)
Mercenaria mercenaria (Linnaeus)
Cerastoderma sp.

The total assemblage and the relative abundances give a very Yorktown aspect. The presence of Anadara cf. A. idonea, Glycymeris cf. G. subovata, and Chlamys decemnaria increase the probability that it is low in the Yorktown, and hence low within the upper Miocene. The list is not so long, nor the preservation so good that the possibility of an upper Saint Marys (upper middle Miocene) can be excluded.

Two microfossils were recovered from the middle of Macks exposed 50 feet north of the railroad overpass over U. S. 401 east of Fuquay Springs. P. M. Brown, U. S. Geological Survey, identified them as Rotalia beccarri linnaeus, var., and an instar (molt) of Hemicythere conradi. Both fossils have a time range from late Miocene into Pleistocene. But there is always the possibility of contamination when so few fossils are recovered.

A three- to four-inch thick discontinuous layer of buhrstone occurs 6 to 12 inches above the base of the Macks. It occurs in less than 5 percent of the outcrop area of the Macks. Some of this material occurs in tabular fossiliferous chunks 1 to 6 feet long. Nonfossiliferous material commonly occurs as rounded pebbles and boulders at or just above the base of the Macks. The fossiliferous buhrstone seems to be, on lithologic grounds, the same as the Eocene deposits reported from Lillington and Spout Springs in Harnett County, from Clayton in Johnston County, and from Auburn in Wake County (Richards, 1950, p. 14). In many places it is a hash of broken shells, all completely replaced by silica, and of external molds.

Fossils were found in this discontinuous buhrstone layer about 6 inches above the base in a well located about 0. 6 mile north of road 1302 from the junction of Johnston County roads 1303 and 1305. The fossiliferous material was 5. 5 feet below the surface. Fossiliferous float is common in a field one mile south from the junction of Johnston County road 1313 and the county line road, then west 3/8 mile on Harnett County road No. 1505 and 1/8 mile south of 1505.

There is no clear-cut contact between the Macks Formation and the underlying Eocene(?) material. Because this older material is discontinuous and patchy, of uncertain thickness, and indurated only in part, it is included within the Macks. This material is not in the type section of the Macks and need not be included within the formation. In this study it is included for convenience only.

Pinehurst Formation

In the area between Fuquay Springs (altitude 420 feet) and Benson (altitude 280 feet) the Macks is overlain by sediments consisting of a mixture of gravel, sand, and clay with only a little silt (Table 1). The proportions of each grade size change rather abruptly both horizontally and vertically. These sediments are not as variable as those of the Tuscaloosa or Black Creek Formations, but they are much more variable than those of the Macks. The lithology and geologic setting are similar to those of the Pinehurst Formation of Conley (1962). But we have not traced these sediments to the area where he mapped Pinehurst and our correlation is tentative. We believe that Pinehurst is more applicable than the term "high level" of Mundorf (1946) and Richards (1950), or the Citronelle of Doering (1960). The Pinehurst is the Lafayette of Stephenson (1912) that was later abandoned.

On the Neuse-Cape Fear divide from elevations of about 420 to about 280 feet there are at least three scarps that separate the divide into progressively lower levels. There is a weakly expressed scarp with a toe altitude of about 400 feet separating two levels near the U. S. 401 - railroad overpass east of Fuquay Springs and west of Willow Springs. Another scarp just west of route 55 at Kennebec with a toe altitude of about 350 feet separates 350-340-foot level from a 390-380-foot level. On the high ground west of highway 55, it is easy to trace the lower surface across the Neuse-Cape Fear interstream divide into the Kenneth Creek valley, part of the Cape Fear drainage. We have crossed this scarp at 350 feet with a drill traverse, but more work in the area is needed to make sure sediments east of the scarp truncate and overlie those to the west. There is so little difference in lithology across the scarp that we cannot separate two sediments on this basis.

West of the Plain View Church in Johnston County is a third scarp with a toe altitude of about 325 feet (Figure 3). This location is on road 1313 north of the Harnett-Johnston County line road. The top of the scarp is about 340 feet and it slopes down to 320 feet in less than 1/8 mile. The sediments east and west of the scarp have very similar lithologies; there is not enough difference between hand specimens to separate them. Yet in this area sediments east of the scarp are inset below sediments to the west and the Macks is thinner immediately east of the scarp. The scarp is not the result of faulting, but it is an erosion feature.

The scarp identified at the Plain View Church also occurs northwest of the junction of route 50 and 42 in Johnston County. County road 1545 climbs this scarp where the road crosses the Johnston-Wake County line. The scarp is well expressed southeast of Drug Store on Johnston County road 1010.

The sediments seem to change very little across these scarps in the Pinehurst. But these stepped levels have considerable geomorphic and sedimentological interest. For this reason we propose that sediments occurring between these scarps be given informal member status until their true relations can be worked out. We propose to use the names Piney Grove member for sediments between altitudes of 350 and 325 and Plain View member for sediments below 325 feet and above 280-270 feet. The relations between these members is shown in Figure 6. It should be understood that these terms are used on an informal basis. For this reason, the word "member" is not capitalized here.

Piney Grove member. We have not studied the Piney Grove member throughout its areal extent on the Neuse-Cape Fear divide. We are not justified in saying much about it at this time. The following discussion will be concerned primarily with the Plain View member of the Pinehurst although much that will be said about the Plain View applies to the Piney Grove member.

Plain View member. The contact between the Plain View and the Macks is abrupt with a local relief of 15 feet plus (Figure 4). The

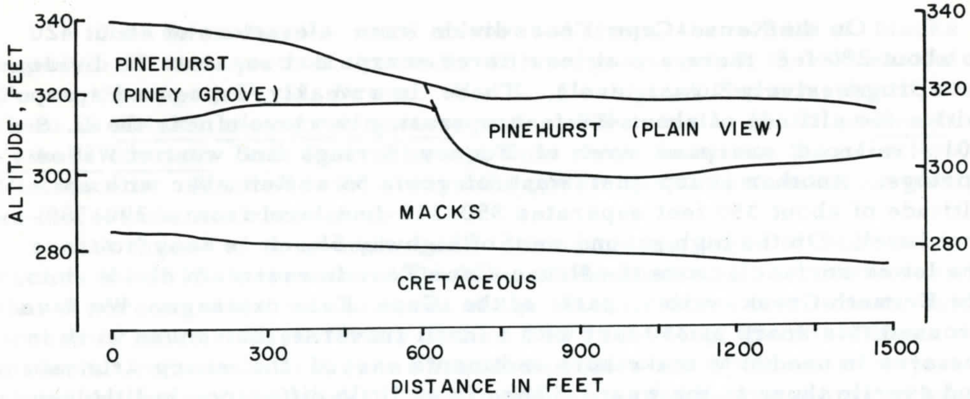

Figure 6. Relations of the Plain View and Piney Grove members of the Pinehurst Formation at the Plain View Church, Johnston County, North Carolina.

greatest concentration of gravel usually occurs a foot or two above the contact. The nature of the contact and the sedimentary structures of the Plain View are well expressed a few yards north of Macks crossroads (Figure 4). Sedimentary structures are poorly preserved and measurements of dip angles and directions are difficult, often impossible, to do with any degree of confidence. Many of the sedimentary structures are large scale cut and fill rather than the smaller cross bedding features.

Gravel is most abundant near the base but pure beds are rare. Clay beds are also rare and usually are mixed with varying amounts of coarse sand. The most clayey beds occur near the top of the member. Combined silt and clay contents average about 20 percent of the sediment (Table 1). Coarse and medium sand predominate and the medium sands are subrounded.

The Plain View in the center of the divides has distinctive color zones in the upper 20 to 25 feet. Soils are about 10 feet thick, well drained, and have the clay maximum in the B horizon 4 to 7 feet below the surface. Plinthite (Soil Survey Staff, 1960), an iron rich material that hardens irreversibly on exposure to air, is a very common component of the B horizons. The soil grades into variegated yellowish brown, pale brown, and white (10YR 5/6, 6/3, 8/2) sediments 5 to 10 feet thick. Red mottles (2.5YR 5/8) increase in abundance at depths between 15 and 25 feet. These sediments may be red when mixed on an auger but they are always mottled with gray and white. These red or mottled red, yellowish brown, and gray sediments grade at depths of 20 to 25 feet to mottled yellowish brown and gray (10YR 7/2) or gray sediments.

The contact between the Plain View and Macks is sharp and distinct because there is an abrupt change in lithology. But there is no apparent change in weathering of the sediments across the contact. In drill holes where the Plain View is mottled yellow and white at its base the underlying Macks generally is mottled yellow and white; if the Plain View is yellowish brown, the Macks generally is yellowish brown. The Macks may grade downward into greenish gray (5GY 5/1) sediments, but the color at the top is always similar to the overlying Plain View. If much subaerial weathering occurred between erosion of the Macks and deposition of the Pinehurst there should be some evidence of differential weathering or soil formation. We have found no hint of a soil profile or a weathering zone related to a soil profile at the top of the Macks. Apparently the erosion surface at the top of the Macks was rapidly buried by the Pinehurst sediments.

Origin and Age. Pusey (1960, p. 17) believes that most of the post-Miocene sediments in the area are fluvial, but most of the evidence for this origin for the Pinehurst is either not decisive or it is negative. Sediments are nearly massive but have indistinct horizontal and cross bedding. These could be marine or fluvial features. There is no evidence suggesting an eolian origin. Large cut and fill structures, the rough erosional contact at the base, the stringers or thin lenses of gravel throughout, and the variable occurrence of gravel beds near the base suggest a fluvial origin. Probably the best evidence of a nonmarine origin for the Pinehurst is the absence of any sign of fossils. We have not found a fossil cast or external mold. This may be negative evidence, but as Grabau (1925, p. 655) stated, "Such absence (of organic remains or their impressions) suggests a subaerial rather than a subaqueous origin for the deposit, and as such it should be considered unless other unmistakable characteristics point to a subaqueous (marine or lacustrine) origin."

Members of the Pinehurst are separated from the Macks by an erosional contact and they are post-late Miocene. The question is how much post-late-Miocene. Unfortunately, there is little direct evidence suggesting an answer, but there is some evidence that will allow us to formulate two mutually excluding hypotheses.

The first hypothesis is that the Pinehurst and Macks are totally unrelated sediments. There is no relation between events that resulted in the Macks and subsequent events that resulted in deposition of the Pinehurst. This would allow the Pinehurst to range in age from Pliocene to Pleistocene. There is no good evidence against this time relation between these two sediments. The only possible exception is that we have never found evidence of pre-Pinehurst weathering in the Macks. This may mean either that any such weathering was removed before the Pinehurst was deposited, or the Macks was never exposed to subaerial weathering.

The second hypothesis is that the Pinehurst and Macks are different parts of one general cycle of marine transgression and regression. The Macks is a marine sediment related to transgression, and the Pinehurst is the fluvial sediment related to regression. Evidence favoring this type of interpretation is the rough erosion surface at the top of the Macks, the apparent different base levels of erosion at the base of the Pinehurst members, and the apparent post-Pinehurst weathering across the contact between the Pinehurst and the Macks. As the sea withdraws, streams flowing across the old ocean floor would locally erode this surface. If a regression is made up of several minor withdrawals and still stands the erosion surface cut into the sea floor could cut to several levels. The contact between the Macks and the Pinehurst fits these features. See Figures 3 and 4. If rapid deposition of sediment followed withdrawal of the sea there should be little difference in weathering across the contact between the two sediments. Most or all of the weathering would occur after deposition of the younger sediment. This is the apparent relation between the Pinehurst and the Macks.

At the present time we do not have enough evidence to reject either hypothesis. If the Macks and the Pinehurst are parts of the same broad cycle, then the Pinehurst may well be as old as late Miocene, or possibly Pliocene. If they are totally unrelated, it is unlikely that the Pinehurst would have been deposited during late Miocene, and it therefore is Pliocene or Pleistocene. No greater accuracy in dating is possible at this time.

"Brandywine Formation"

The nomenclature of surficial formations in the Atlantic Coastal Plain is in a state of flux (Colquhoun, 1962, 1965; Colquhoun and Duncan, 1964; Oaks and Coch, 1960). Names are changing as investigators critically study surficial sediments. Historically, in this area of North Carolina, the Brandywine Formation has been applied to materials that occur between altitudes of about 270 to 220 feet (Cooke, et al, 1943). We are tentatively using about the same definition for the "Brandywine Formation" but with some reservations. We can find the scarp separating the Brandywine and Coharie geomorphic surfaces, and we have traced it across the Neuse River watershed. But on the Neuse-Cape Fear divide we do not have strong evidence that sediments under the Brandywine and Coharie Terraces are different formations. Our evidence at this time suggests that one formation occurs between an altitude of 270 feet and the Surry scarp. There are regionally traceable scarps cut into this formation, but at the classical break from the Brandywine to the Coharie, or the Coharie to the Sunderland, we cannot find strong evidence of two formations. We need additional work on this aspect, but we are using the term "Brandywine Formation" with the reservation that it may need to be renamed when other evidence is collected.

It is difficult, if not impossible, to separate the Pinehurst and "Brandywine" Formations strictly on the basis of lithology. A medium loamy sand that is nearly all quartz and kaolinite looks like any other medium loamy sand that is nearly all quartz and kaolinite. The great similarity of the Pinehurst and "Brandywine" sediments does not mean that they are not separated in space and time. If you cannot separate these sediments on the basis of lithology, then what criteria should be used? We map the "Brandywine" and Pinehurst on the following basis.

In areas, the Macks Formation crops out on the scarp separating the two formations (Figures 2, 3). Topographic features must be used at the boundary between the Pinehurst and "Brandywine." Small depressions (Carolina Bays) commonly mark the contact, and there is a distinct flattening of slope. Separation on the ground is best accomplished by mapping the toe of the scarp and checking for Macks or Cretaceous formations. At this point it may be logical to ask whether we are separating formations strictly on the basis of surface or topographic features. We separate the "Brandywine" from the Pinehurst only because we can prove within reason that the "Brandywine" either overlies or cuts out the Pinehurst and the Macks (Figures 2, 3), or both. If these criteria are used, why not designate the Piney Grove and Plain View members as formal units? Our answer is that we have detailed information on the Plain View and Piney Grove relations in only one area; we have it on the Pinehurst-Brandywine in several areas.

The purist may never be satisfied with this manner of distinguishing the high terrace sediments in North Carolina. These sediments are not different enough to allow separation based solely on lithology. But, when the relations are thoroughly studied in the field, it is often possible to show that sediments are separated in time and space. To combine formations such as the Pinehurst and "Brandywine" because they do not differ greatly in lithology is to ignore a tremendous amount of evidence.

The "Brandywine" sediments are very similar to the Pinehurst in silt and clay content, and dominant sand fractions (Table 1). Gravel beds are common near Benson, and some are being used for road metal. An excellent outcrop of gravel is on Harnett County road 1809, 0.15 mile west of the Harnett-Johnston County line. The "Brandywine" in some roadcuts has crossbedding and cut and fill structures, but normally it is massive. A typical section of these sediments is exposed in the railroad cut about 3/4 mile northeast of the Benson railroad station or 100 feet north of the U. S. 301 railroad overpass east of Benson. The section on the northwest bank is:

Depth, feet	Description
"Brandywine Formation" 0-7	Soil profile; base color yellowish red (5YR 5/6); few to common quartz pebbles up to 3/4 inch long; Brandywine Formation.
7-9.3	Yellowish brown (10YR 5/6) sandy loam; massive; few to common quartz pebbles up to 3/4 inch long; gradual lower boundary.

9.3-14.0	Brownish yellow (10YR 6/6) coarse sandy loam; many quartz pebbles; individual pebble beds 3-4 inches thick can be traced horizontally along the cut 10 to 15 feet; massive; this bed can be traced across the cut; abrupt lower boundary.
14.0-15.0	Brownish yellow (10YR 6/6) coarse sandy loam; many thin, less than 1/16 inch, dark yellowish brown (10YR 3/4) horizontal streaks; few pebbles.
Tuscaloosa(?) Formation	
15.0+	Weak red (10YR 5/2) massive clay, common light gray (5Y 7/1) mottles; base of observation 17 feet.

The distribution of the "Brandywine" near Benson is shown in Figure 2. Although these sediments are on primary interstream divides, they also occur as river valley terrace sediments in the Black Creek valley (Figures 2, 3). Near its contact with the Pinehurst the "Brandywine" overlies the Macks and it is, in places, thin and discontinuous. But, as the erosion surface at the base of the "Brandywine" cuts through the Macks into Cretaceous materials, the sediment thickens. The truncation of Macks is clearly shown in two traverses across the upper edge of the Brandywine (Figure 7). The traverse along Johnstone County road 1331 crosses the "Brandywine" - Pinehurst contact at an angle almost parallel to the contact. It is an excellent place to follow the progressive thinning of the Macks as it is cut out by the erosion surface at the base of the "Brandywine."

The contact between the Pinehurst and "Brandywine" is not always sharp and easily determined. This is especially true on the Neuse-Cape Fear divide north of Benson. The exact contact as drawn (Figure 3A) may be off slightly, but there is too much evidence of these sediments being separated in time and space to combine the Pinehurst and "Brandywine" into one formation. The "Brandywine" is not a downthrown fault block of the Pinehurst (Figures 3, 7) and there is no evidence that the Pinehurst drapes across the erosion surface that cuts out the Macks. Thus the "Brandywine" is post Plain View member of the Pinehurst.

In this same area of North Carolina Doering (1960, p. 192) believed that the Citronelle Formation was continuous from Fuquay Springs to south of Benson. He stated (p. 191), "In central North Carolina --- the 'Lafayette' is the Citronelle. Also included in this area are the deposits in the type area of Stephenson's 'Coharie' which extended eastward between the valleys of Cape Fear and Neuse Rivers to the vicinity of Magnolia." Doering apparently included the Macks, the Pinehurst, the "Brandywine," and some of the Cretaceous materials in his Citronelle (compare thickness of sediments in our Figure 3 with Doering's

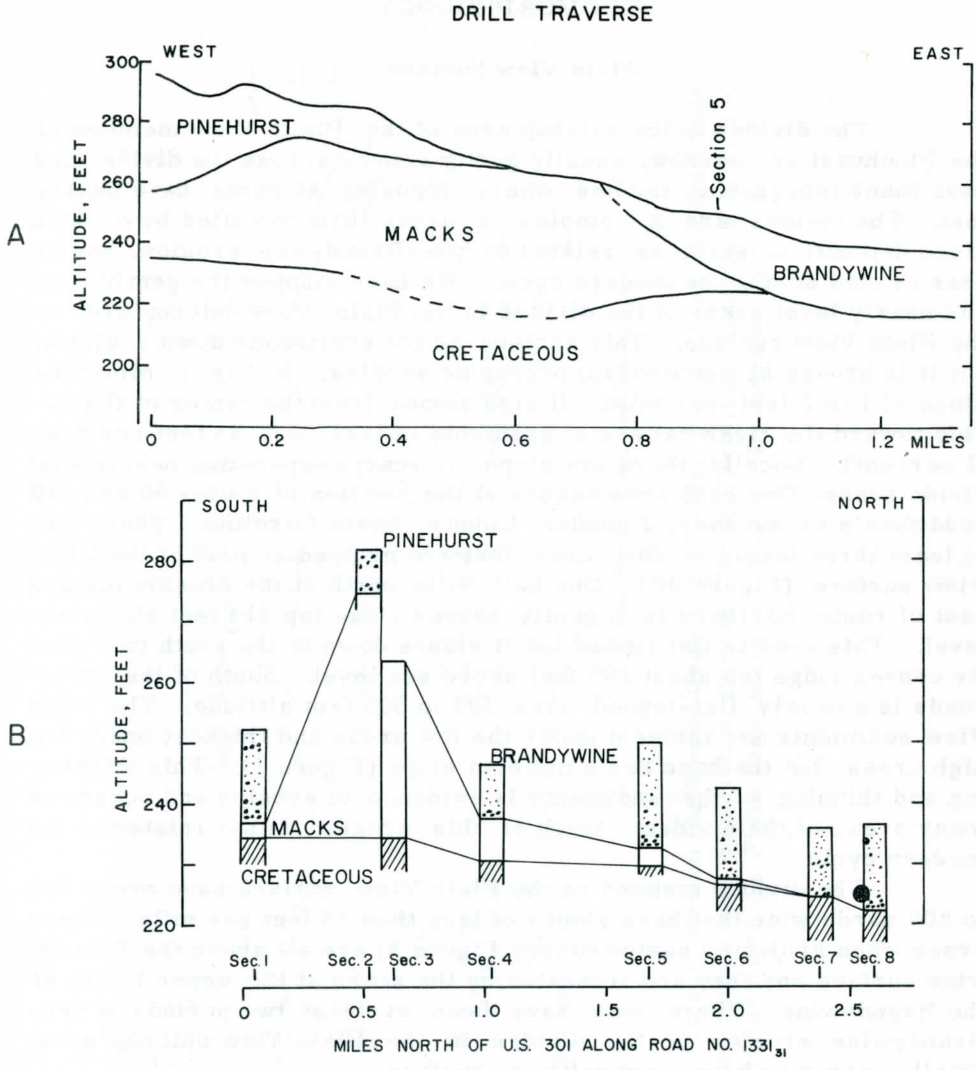

Figure 7. A. Drill traverse at right angles to road no. 1331 showing relations between the Pinehurst, Macks and "Brandywine" Formations north of Benson, North Carolina.
B. Sequence of sediments along Johnston County road 1331 north of Benson, North Carolina. Traverses A and B cross at section 6.

figure 8). Based upon our evidence, the Citronelle of Doering in this area should be correlated with the Pinehurst only after it has been redefined to exclude the Macks and what we are tentatively calling the "Brandywine."

GEOMORPHOLOGY

Plain View Surface

The divides in the outcrop area of the Plain View member of the Pinehurst are narrow, usually gently convex across the divide, and have many topographic saddles where opposing streams have nearly met. The divides are a complex of areas little modified by erosion since deposition, surfaces related to pre-Brandywine erosion, and areas eroded during the modern cycle. We have mapped the gently convex nearly level areas of the divides in the Plain View outcrop area as the Plain View surface. This surface is not continuous down a divide, but it is broken by numerous topographic saddles. It has a minimum slope of 1 to 2 feet per mile. It also slopes from the center of the divide toward the river valleys at gradients of less than 53 feet per mile (1 percent). Locally there are slopes or scarps separating nearly level divide areas. One such area occurs at the junction of routes 50 and 210 at McGee's crossroads, Johnston County, North Carolina. There are at least three levels in this area that are mapped as part of the Plain View surface (Figure 8C). One half mile north of the crossroads and east of route 50 there is a gently convex ridge top 314 feet above sea level. This area is flat topped but it slopes down to the south to a gently convex ridge top about 295 feet above sea level. South of the crossroads is a nearly flat-topped area 303 to 305 feet altitude. The Plain View sediments are thinnest under the low areas and thickest under the high areas, but the base has a uniform slope (Figure 3). This thickening and thinning of the sediments is evidence of erosion and occurs in many areas of the divides. Much of this erosion is not related to the modern cycle.

The divides mapped as the Plain View surface have areas 100 to 200 yards wide that have slopes of less than 53 feet per mile. These areas when projected eastward (see Figure 8) are all above the Brandywine surface and they are truncated by the scarp at the upper limits of the Brandywine. There may have been at least two periods of pre-Brandywine erosion of the divides in the Plain View outcrop area. Small areas may have a depositional surface.

Brandywine Surface

The Brandywine surface is the level to nearly level depositional surface at the top of the "Brandywine Formation." It occurs between altitudes of about 275 or 270 to about 230 feet on the Neuse-Cape Fear divide. It is truncated locally by topographic saddles, the Coharie surface, and modern drainage. The Brandywine has a downdip slope of about 15 feet per mile from its junction with the Pinehurst Formation to the city of Benson, a distance of about 2 miles. South of Benson it has a slope of one to three feet per mile. A discontinuous scarp at about

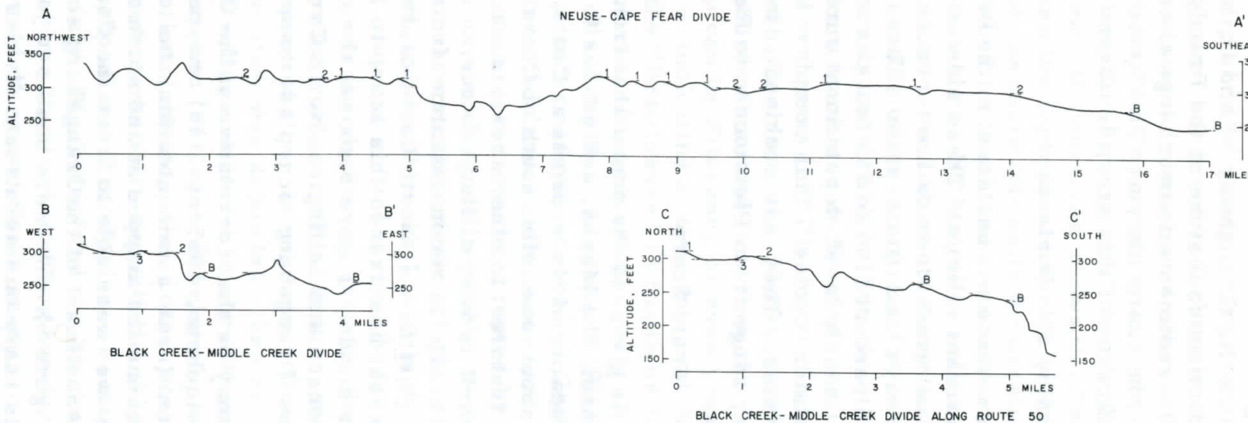

Figure 8. Geomorphic surfaces on the Neuse-Cape Fear divide, Black Creek-Middle Creek divide and along route 50 north of Benson, North Carolina. Numerals 1, 2, and 3 refer to levels of the Plain View surface. B is the Brandywine surface.

250 to 245 feet marks the change in gradient on the Brandywine surface. This change is clearly shown near Benson on the Neuse-Cape Fear divide; in Benson on N. C. highway 50 the scarp is well defined about 1/2 block north of the junction of N. C. highway 50 and U. S. 301. This scarp is a common but discontinuous feature of the Brandywine surface in the Neuse watershed. The sediments do not change character across this scarp, but often above the scarp they are thin and discontinuous. No explaination of the significance of this scarp is offered at this time.

Valley Side Surfaces

The most complex surface or surfaces in the Benson area are on the side slopes in the stream valleys. These side slopes truncate the succession of deposits and grade down to low terraces in the valley and to the modern drainageways and flood plain. These side slopes have inclinations of 2 to 15 percent (106 to 795 feet per mile) and even where they grade to a low, nearly level depositional surface they may have been eroded during later cycles. This complex is collectively called the valley-side surfaces. They are erosional, and locally depositional surfaces that may range from Pleistocene to Recent.

Coats Scarp

The name Coats is given to the scarp that truncates the Plain View member of the Pinehurst, the Macks, and grades to the top of the "Brandywine." The type locality of the scarp is at Coats, North Carolina, on N. C. highway 55 about one mile south of Coats. In this area it is a distinct topographic feature. In other areas, such as along N. C. highway 50 north of Benson, it is very difficult to see.

We have traced the scarp in reconnaissance from a point about 6 miles north-northeast of Fort Bragg, North Carolina, to Coats, North Carolina. More detailed work has traced this scarp to Benson and on northeast to the Neuse-Tar divide. Figure 5 shows the distribution of the Coats scarp between Benson and Lillington, North Carolina, and the approximate location of the Orangeburg scarp as mapped by Johnson and Du Bar (1964).

The Coats scarp may be the correlative of the Orangeburg or Citronelle escarpment (Colquhoun, 1965, p. 119) mapped by Johnson and Du Bar (1964). Johnson (oral communication) believes that the Orangeburg fades out and cannot be mapped at and north of Fayetteville. In a reconnaissance study we were able to trace the Coats scarp to a point about 6 miles north-northeast of the Orangeburg scarp as mapped by Johnson and Du Bar (Figure 5). We were unable to join the scarps.

The toe of the Coats scarp on interstream divides is the uneroded top of the "Brandywine Formation." Although often thin and discontinuous, the top of the "Brandywine" has a maximum altitude of 280 to 270 feet on interstream divides; rarely does it go as low as 250 feet unless eroded. Johnson and Du Bar (1964) mapped the toe of the Orangeburg at altitudes ranging from 250 and 220 feet. Colquhoun (1965, p. 21) mapped the toe of the scarp as low as 210 feet. We believe that the Orangeburg scarp and the Coats scarp represent at least part of the same general feature but proof is lacking at this time. Part of the apparent difference may be a matter of concept of the scarp and its relation to sediments. The Coats scarp and the Citronelle escarpment as mapped by Doering (1960) in central North Carolina are not the same feature, however. If later work shows the Coats to be the same as the Orangeburg, then the name Coats should be dropped.

There is one more difficulty in correlating the Coats and Orangeburg scarps. Work in South Carolina indicates that the Orangeburg is a late Miocene sea cliff. No Miocene sediments have been found west of the scarp, and Miocene sediments occur east of the scarp (Colquhoun, 1965, p. 19). On this basis interpretation of a late Miocene age for the Orangeburg scarp is reasonable. But the Coats scarp is post-late Miocene because it truncates sediments containing lowest upper Miocene fossils. It also truncates the Pinehurst Formation (Figures 4, 8). In this area of North Carolina the Macks was deposited, then the Pinehurst, the Pinehurst dissected, and then the Coats scarp was cut. Thus the Coats scarp can be Pliocene, or even younger.

Evidence indicating a time interval between deposition of the Pinehurst and the "Brandywine" Formations is found in the relief of the associated surfaces. Measurements of relief and cumulative slope groups (Figure 9) of divides in areas of Plain View and "Brandywine" outcrop show distinct changes across the Coats scarp. These changes are visible to even the casual field observer. The divides in the Plain View outcrop area are narrow, interrupted by many topographic saddles (Figure 4), and have undergone possibly two periods of erosion since deposition. By contrast the divide of the Brandywine near Benson is relatively smooth, and level areas 1/4 mile or more wide are frequent. This difference in local relief of the divides and other characteristics of these surfaces is the result of greater dissection of the Plain View than the Brandywine surface. This, in turn, indicates a time difference, although the amount of time is unknown. One interpretation of events is that the Plain View was deposited, then erosion surfaces cut into the member so that valleys were cut in about their present location. After these initial erosion surfaces developed, many of them crossing the present interstream divide, the Coats scarp was cut. Later the "Brandywine" sediments were deposited and the scarp modified so that it sloped to the top of the Brandywine. Because this scarp cuts out 30 or more feet of the Pinehurst and the Macks Formations, there must have been some time involved, but how much is unknown.

If the Orangeburg and Coats scarp are the same feature or parts of the same feature, there is one question that must be answered. Can one feature be cut in South Carolina in late-Miocene and the same feature in North Carolina in post-Miocene time? Only additional work can

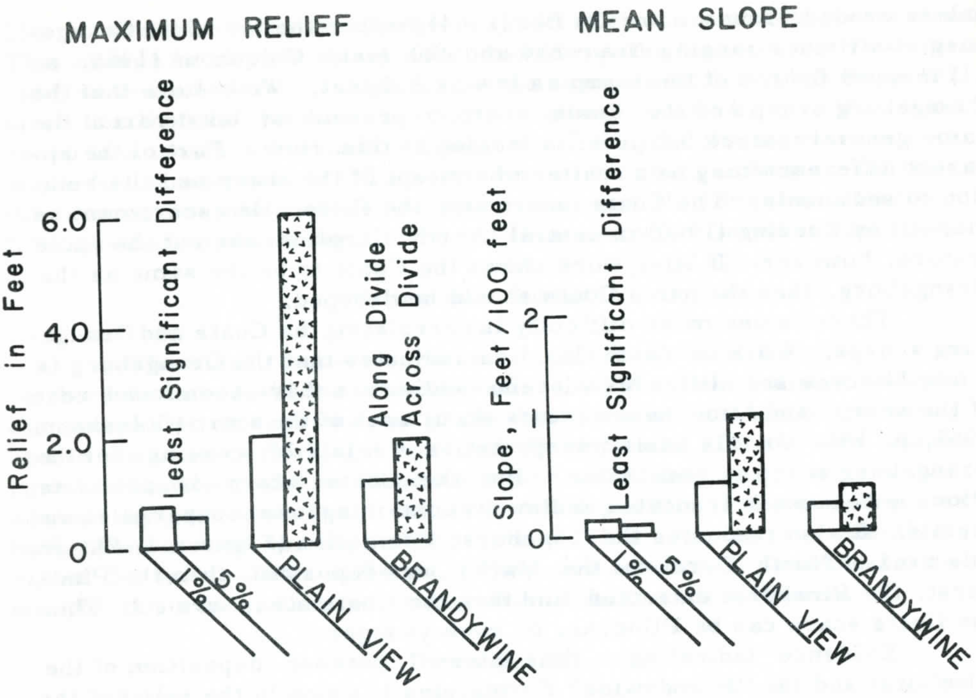

Figure 9. Maximum relief and mean slope of divides in areas of the Plain View and Brandywine outcrop. Measurements were made along 600-foot lines with the center point on the divide axis.

solve this and other related questions, but at least it should be interesting to follow the ideas that will develop from what are now apparent anomalies.

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VIRGINIA METAMICT MINERALS: ALLANITE

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ABSTRACT

An X-ray diffraction study was made of heat-treated metamict allanite. Indexed X-ray powder data are given for allanite which has a structure like epidote and a = 8.91 Å, b = 5.72 Å, c = 10.13 Å, β = 115°. At temperatures above about 750° C other phases begin to develop from the decomposition of the mineral. These include ceric oxide, magnetite, anorthite, and an apatite-like silicate with a = 9.56 Å and c = 7.04 Å. Indexed X-ray powder data for this silicate are given. Over twenty-five localities for Virginia allanite are considered, and in every case where specimens could be obtained the mineral was verified by X-ray analysis.

INTRODUCTION

Because of difficulties which exist in distinguishing allanite from other metamict minerals, especially chevkinite and perrierite, this study was undertaken to verify reported occurrences of the mineral, and to obtain X-ray data by which it might easily be identified. Since allanite is usually metamict, considerable difficulty has been encountered in obtaining reliable X-ray data for it. Data in the literature show wide differences, especially for specimens heated at various temperatures. In a preliminary note the writer reported that with different heat-treatments at least three X-ray patterns can be obtained from the mineral (Fitzgerald and Mitchell, 1961). These patterns are interpreted in this study. The results obtained from a similar study of perrierite and chevkinite are reported elsewhere (Mitchell, 1966).

Acknowledgments

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Table 1. X-ray Powder Data for Heated Allanite (A type pattern). Filtered Copper Radiation. Cameras of 11.46 cm Diameter.

hkl	d (calc.) Å	d (meas.) Å	I (obs.)
001	9.18	9.39	ms
100	8.08	8.04	mw
$\bar{1}01$	7.96		
101	5.09	5.12	m
$\bar{1}02$	5.00		
011	4.85	4.86	vw
110	4.67		
$\bar{1}11$	4.64	4.65	s
002	4.59		
$\bar{2}01$	4.45		
200	4.04	4.03	w
$\bar{2}02$	3.98		
111	3.80	3.79	w
$\bar{1}12$	3.76		
012	3.58		
$\bar{2}11$	3.51	3.52	s
102	3.42		
$\bar{1}03$	3.37		
210	3.30	3.30	w
$\bar{2}12$	3.27		
201	3.23	3.23	w
$\bar{2}03$	3.17		
003	3.06		
$\bar{3}01$	2.94	2.95	vs
112	2.93		
$\bar{3}02$	2.92		
$\bar{1}13$	2.90		
020	2.86	2.86	m
211	2.81	2.81	w
$\bar{2}13$	2.77		
021	2.73	2.74	mw
013, 120	2.70		
300, $\bar{1}21$	2.69	2.68	mw
$\bar{3}03$	2.65		
$\bar{3}11$	2.62	2.61	m
$\bar{3}12$	2.60		
202	2.54	2.55	m
		2.43	w
		2.33	w
		2.17	w
		2.14	mw
		2.06	w
		1.99	vvw
		1.91	mw
		1.87	vw
		1.67	vw
		1.64	mw
		1.60	w
		1.55	w
		1.47	w
		1.43	w
		1.40	vw
		1.38	vvw

X-RAY DIFFRACTION DATA

Although the reflections were not indexed, some of the earliest X-ray powder data reported for allanite are those of Kauffman and Jaffe (1946), Takubo and Ueda (1948), Berman (1955), and Umegaki and others (1957). After the determination of the structure of allanite (Ueda, 1955), Ueda and Korekawa (1954, 1955) and Ueda (1957) published indexed data for patterns with that structure. On the other hand, some of the aforementioned references, as well as data reported by Lima-de-Faria (1958), Fitzgerald and Mitchell (1961), Khvostova (1962, p. 58), and Kumskova and Khvostova (1964), show that many allanite patterns, especially for materials heated at high temperatures where new phases form, cannot be indexed simply by considering the allanite structure.

In a preliminary X-ray study of heat-treated allanite from near Peaksville, Bedford County (Fitzgerald and Mitchell, 1961), it was observed that three distinct patterns, designated A type, B type, and C type, can be obtained from the material when heated in air. The phases yielding these patterns have subsequently been determined.

A Type

This pattern, which is similar to epidote, is the true allanite structure. The indexed data in Table 1 represent averaged values derived from the measurements of five separate but nearly identical films, made in two cameras (11.46 cm diameters) with CuKα radiation. The samples were from the Peaksville specimen and were heated in air from half an hour to 6 hours within the range of 600° C to 900° C. The lines were indexed satisfactorily using the lattice constants a = 8.91 Å, b = 5.72 Å, c = 10.13 Å, β = 115°, a:b:c = 1.558:1:1.771. All possible calculated interplanar spacings allowed for the $P2_1/m$ space group are reported through 2.54 Å. The values in Table 1 correspond well with indexed values reported by Ueda and Korekawa (1954, 1955) and Ueda (1957), although there are some minor differences in the indexing. Ueda (1957) also noticed slight lattice contraction with heating. There is a good correlation between the Virginia data and values published by Kauffman and Jaffe (1946) and Berman (1955) for untreated non-metamict allanite, as well as values published by several others for heat-treated materials.

This A type pattern was obtained for the Peaksville material when heated in air for half an hour at all temperatures through 925° C. The quality of the patterns and number of lines increased with increasing temperature. Samples heated at all time intervals at higher temperatures produced the C type pattern. The A type pattern was also present when samples were heated 24 hours at 800° C, however, at 900° C the B type pattern began to form after 1 hour, and was the characteristic pattern in samples heated from 4 to 24 hours at this tempera-

Table 2. X-ray Powder Data for Apatite-like Silicate Formed from Allanite at High Temperatures. Filtered Copper Radiation. Cameras of 11.46 cm Diameter.

hk·l	d (calc.)Å	d (meas.)Å	I (obs.)
10·0	8.28	8.35	vvw
10·1	5.36	5.40	vvw
11·0	4.78		
20·0	4.14	4.14	w
11·1	3.95	3.93	*w
20·1	3.57		
00·2	3.52	3.52	w
10·2	3.24	3.24	*m
21·0	3.13	3.13	*ms
21·1	2.86	2.86	s
11·2	2.83		
30·0	2.76	2.76	vw
20·2	2.68	2.69	mw
30·1	2.57		
22·0	2.39	2.38 ?	vvw
21·2	2.34		
31·0	2.30	2.29	vvw
22·1, 10·3	2.26		
31·1	2.18	2.20	vvw
30·2	2.17		
11·3	2.11	2.10	*w
40·0	2.07	2.07	vvw
20·3	2.04		
40·1	1.99		
22·2	1.98	1.98	m
31·2	1.92	1.92	m
32·0	1.90		
21·3	1.88	1.88	m+
32·1	1.83	1.84	m
41·0	1.81	1.81	m-
30·3	1.79		
40·2	1.78	1.78	m
00·4	1.76	1.76	w
41·1	1.75		
10·4	1.72		
22·3, 32·2	1.67	1.69	vw
		1.64	w
		1.56	vvw
		1.53	vvw
		1.50	w
		1.49	*m
		1.46	w

* At these positions there is interference from either anorthite or magnetite.

ture. Unfortunately the above conditions for the break-down of the allanite A type structure are not constant. Subsequent studies of allanite from various other localities did not yield the same results, especially for samples that are completely metamict or quite weathered. At 800° C the writer has obtained each of the three types of patterns after heating half an hour. On the basis of this study it seems that 750° C is the maximum temperature to be used for the heat-treatment of allanite in air if the true structure is to be obtained. Kumskova and Khvostova (1964) found their allanite data began to change above 800° C. Berman (1955) suggested that unreliable data were obtained when samples were heated above 850° C. Thermal studies of allanite by various workers (Kauffman and Dilling, 1950; Orcel, 1953; Ukai, 1955; Kakitani and Kato, 1956; Khvostova, 1962, p. 72) have shown wide differences in the temperature of the break-down of allanite (usually between 850° C and 1000° C), depending upon the degree of metamictization, composition of specimen, and physical-chemical factors for the deposit considered.

C Type

This pattern, formed by heating allanite at very high temperatures in air, is a mixture of three phases consisting of a member of the spinel group, a silicate with the apatite structure, and minor plagioclase close to anorthite. A detailed study of films made of the Peaksville material showed the spinel-like mineral is close to magnetite. The samples are attracted to a magnet and a = 8.40 Å. The major reflections observed are 2.96 Å (220), 2.53 Å (311), 2.10 Å (400), 1.72 Å (422), 1.62 Å (333, 511), and 1.49 Å (440). The apatite-like silicate is also a major phase in the pattern. The observed data for this silicate, given in Table 2, were obtained by averaging values from four separate films made of materials heated at 1000° C. The lattice constants, a = 9.56 Å, c = 7.04 Å, c/a = 0.736, and the space group $P6_3/m$, allowed the observed values to be indexed. Unfortunately, as indicated in Table 2, there is some uncertainity about some of the reflections near positions for magnetite and anorthite. It is interesting to note that Rudneva and others (1962) have reported a fluorine-rich cerium britholite from furnace slags which is very similar with a = 9.54 Å, c = 7.01 Å, and c/a = 0.735. The anorthite phase in the C type pattern is relatively minor, although usually present. The most distinct anorthite lines were noted in samples heated for 24 hours at 1000° C. Anorthite commonly forms when other members of the epidote group are heated at 1000° C. In this study it was formed from epidote, clinozoisite, and piedmontite, while no apatite structure or magnetite were detected in these. While the C type pattern previously has not been defined or interpreted, data similar to it have been listed by Ueda and Korekawa (1955) and Khvostova (1962, p. 58). Although, in the study of Peaksville allanite the C type did not appear until samples were heated above 925° C, subsequent studies of other allanite samples showed it could form as low as 800° C after half an hour. The best films were obtained after heating allanite for 24 hours at 1000° C.

B Type

The most important phases in this pattern are a rare earth oxide and a member of the spinel group. Weaker lines for plagioclase and the apatite-like silicate, characteristic of C type patterns, are also present. The rare earth oxide is close to CeO_2. Samples obtained from heat-treated Peaksville allanite have a = 5.44 Å while chemically pure CeO_2 has a = 5.41 Å (Swanson and Tatge, 1953). The following lines are usually present: 3.14 Å (111), 2.72 Å (200), 1.93 Å (220), 1.64 Å (311), 1.57 Å (222), 1.36 Å (400), 1.25 Å (331), 1.22 Å (420), and 1.11 Å (422). The spinel-like phase is identical to the one in the C type patterns and is probably magnetite, with a = 8.40 Å.

Although in the Peaksville study the B type pattern formed only after prolonged heating at 900° C, specimens from other localities showed this pattern after heating half an hour at 800° C. The chief difference between the B type and C type patterns is that in the former the rare earths exist mainly as oxides while in the latter they are in the apatite-like structure. Apparently the CeO_2 phase forms by slow oxidation at the upper limit for the stability of the allanite phase, while heating at higher temperatures produces the apatite-like silicate phase.

The presence of CeO_2 lines in heated allanite has been noted by Ueda (1957), Lima-de-Faria (1958), Khvostova (1962, p. 58), and Kumskova and Khvostova (1964). High temperature data reported by Lima-de-Faria (1958) and Ueda (1957) match the B type pattern well.

If, in addition to being metamict, the allanite is also considerably weathered, it may be impossible to obtain any of the patterns discussed above. Thin-bladed, weathered allanite from the Champion pegmatite, Amelia County, remained completely amorphous even after heating for 1 hour at 800° C. The pattern obtained after heating 3 hours at 1000° C was a mixture of hematite and anorthite.

VIRGINIA ALLANITE OCCURRENCES

Allanite was known in Virginia as early as 1874. At the present time over twenty-five occurrences have been reported. In order to assemble a comprehensive list of the occurrences the writer utilized several sources of information, including extensive published literature, available museum specimens (especially Lewis Brooks Museum, University of Virginia), and information communicated to him personally. The writer also attempted to visit each locality which came to his attention, although occasionally the attempts were unsuccessful because of lack of sufficient information.

In general allanite in Virginia falls into three broad categories. These include the large masses in pegmatites on the Blue Ridge, the thin-bladed crystals in the non-Blue Ridge pegmatites, especially in Amelia and Bedford Counties, and microscopic accessory allanite in various rock types. Although all the allanite studied is metamict, the large massive pieces from the Blue Ridge seem to be the least affected. No X-ray study was made of the microscopic accessory types, but optical studies show they are generally isotropic.

The occurrence of allanite at the Burley farm, near Amherst, Amherst County (Pegau, 1932, p. 96), was discredited. On the basis of X-ray study the materials were shown to be perrierite (Mitchell, 1966).

In the following presentation, where localities are listed alphabetically according to county, the plan has been to give the original references; to list associated rare minerals, especially where they previously have not been reported; and to give other pertinent data where they might apply. Where locality names are followed by an asterisk (*) the allanite has been verified in this study by X-ray analysis.

Amelia County, Champion pegmatite*. Lemke and others (1952, p. 115) and Brown (1962, p. 69) have reported allanite from the Champion (Jefferson No. 4, Bland) pegmatite. Brown indicated that only one small allanite crystal had been found, and this was not described. The writer found a small amount of much-weathered material identical in habit to the allanite from the Rutherford and John Patterson pegmatites. Heat treatment of this material did not produce the standard allanite data. After heating for 1 hour at 800° C the material remained amorphous; 3 hours at 1000° C produced a mixture of hematite and anorthite. The weathered condition of the sample probably produced these anomalous results. In addition to the typical pegmatite silicate minerals other minerals include fergusonite, rhabdophane (Mitchell, 1965), pyrochlore, microlite, columbite-tantalite, sphene, and zircon.

Amelia County, John Patterson pegmatite*. Sterrett (1923, p. 315) reported allanite on the dumps of the old John Patterson pegmatite. Lemke and others (1952, p. 120) found flattened black crystals of the mineral. The writer found relatively fresh long flattened blades of metamict allanite in rocks on the dumps of the old mine. A small amount of euxenite was also observed. Garnets and apatite were also reported by Lemke and others (1952).

Fontaine (1883) noted allanite crystals up to 15 inches in length, associated with gigantic feldspar crystals, in a pegmatite about 2 miles northeast of the Rutherford pegmatite. This presumably is the John Patterson pegmatite.

Amelia County, Morefield pegmatite. Allanite was identified by Lemke and others (1952, p. 129) in the Morefield pegmatite. They did not describe the mineral. Evidently it is very uncommon since it is not in previous comprehensive lists of minerals from the deposit (Glass, 1935). The writer failed in his attempt to collect the mineral.

Amelia County, Rutherford pegmatite*. Koenig (1882) first reported and chemically analyzed allanite from the Rutherford pegmatite. One crystal measured 0.25 by 1 by 4 inches, and was enveloped by a thin reddish alteration crust. Nearly simultaneously Dunnington (1882) also analyzed Rutherford allanite and mentioned partially decomposed blade-like crystals several inches in length.

Fontaine (1883) further described the Rutherford allanite. He found bladed crystals up to 8 inches long and about a quarter of an inch by an inch in cross section. The crystals, embedded in feldspar and quartz, frequently are altered to a dull ash-gray material sharply distinct from the velvet-black interior. Recent studies by the writer have shown this alteration material is principally bastnaesite. Because the associated minerals at this deposit are so numerous the reader is referred to Glass (1935) for an exhaustive list.

Amherst County, Bunker Hill trail, near Lynchburg Reservoir*. Much allanite occurs in a small deeply weathered pegmatite exposed on the old Bunker Hill trail. Cormack and Stow (1953, p. 3) reported the occurrence, but it has never been described. Massive pieces of allanite over 6 inches long have been found. Much of the material is deeply weathered and some is completely replaced by weathering products. Preliminary studies of the weathering products have shown, among other things, mixtures of quartz, bastnaesite, and possibly cerianite and monazite. Strongly radioactive anhedral pink monazite masses, less than half an inch across, as inclusions in the allanite, are quite numerous. Zircon crystals, less than a quarter of an inch long are present but not common. Also there are kaolinized feldspar masses, kaolinized graphic granite, bluish to milky quartz, large books of altered mica, small garnets, and greenish-black chlorite pseudomorphs after garnet crystals.

Amherst County, Fabers' Mills. Froehling and Robertson (1904, p. 2) indicate that allanite occurs in massive form at Fabers' Mills, Amherst County.

Amherst County, Little Friar Mountain*. A report, including a chemical analysis, was given first for the Little Friar Mountain allanite by Cabell (1874). The locality was not specifically indicated, but was said to be "about 15 miles west of Amherst Court House." Mallet (1877) stated the locality was on the northwestern slope of Little Friar Mountain. He examined over 300 pounds of allanite and also found fergusonite (sipylite), magnetite, zircon, and decomposed feldspar. Weathered crusts of the allanite were analyzed by Santos (1878). He mentioned detached lumps of material, showing rough crystalline faces, up to 4 pounds in weight. Most of the allanite sold by mineral companies in the late nineteenth century, labelled simply Amherst County, is from this deposit. Other labels include the towns of Alhambra or Lowesville. Two specimens in the U. S. National Museum which are probably from this same locality bear the labels, "8 miles west of Massies Mill, Nelson County, Virginia" (USNM 112514), and "Headwaters of Piney River, Nelson County, Virginia" (USNM 65174).

Bedford County. Allanite, especially high in the cerium earths (their oxides greater than 50% of the mineral), was reported from an unspecified locality in Bedford County by Page (1882). The specimen was a compact black mass with a pitchy luster.

Bedford County, north of Chamblissburg*. North of Chamblissburg the writer found two masses of float quartz containing slightly altered allanite crystals ranging from a quarter of an inch to over an inch across. The allanite was found at the edge of a meadow on top of a ridge which is located west of the driveway leading from State Road 616 to the W. E. Dooley place.

The writer visited this area because of specimens in the Lewis Brooks Museum originally belonging to T. L. Watson. One allanite (V2985d), labelled "Powell farm, High Knob, Bedford County, July 21, 1916," is nearly identical to material collected by the writer. A perrierite specimen (V2984d) has the same label. A second perrierite specimen (V2981d) was labelled "Mrs. N. A. McMannaway, Stewartsville, Virginia." According to local residents both Powells and McMannaways lived near the Chamblissburg locality which is at the present Dooley place. Black vitreous garnet and magnetite were also with the McMannaway label.

The writer was unable to find perrierite at the locality.

Bedford County, Mitchell pegmatite*. Allanite in this pegmatite has been described briefly by Dietrich (1963, p. 28). Bent and sporadically broken composite crystals, about a quarter inch by an inch in cross section and over 5 feet long, occur in the quartz-rich zones. Associated minerals include columbite-tantalite (crystals up to 2.5 inches along c), betafite (?), apatite, zircon (small crystals), garnet, beryl, and thulite.

Bedford County, near Peaks of Otter. Allanite is found near the Peaks of Otter, Bedford County, according to Dana (1895, p. 1072). This may be a general reference to one of the more specific localities described in this paper.

Bedford County, Peaksville*. A slightly altered allanite mass, measuring 6 by 4.5 inches, labelled Peaksville, Bedford County, is in the Lewis Brooks Museum collection (4445). Fragments of quartz and somewhat weathered feldspar are attached to the mass. This is the specimen whose X-ray data were described earlier in this paper, and from which Fitzgerald and Mitchell (1961) obtained samples for their preliminary X-ray study.

Brown (1962, p. 186) has reported the possible occurrence of accessory amounts of allanite in the wallrock associated with the Peaksville syenite-alaskite mine, and the Cloes pegmatite mine, both located in the Peaksville area.

Bedford County, near Thaxton. Allanite containing 33% ceria from near Thaxton is mentioned by Sanford and Stone (1914, p. 191). This may be a general reference to one of the more specific localities described in this paper.

Bedford County, Wheatley pegmatite near Moneta*. Somewhat weathered allanite blades, measuring a quarter by half an inch and over 4 inches in length occur in feldspar and quartz masses at the Wheatley pegmatite. Associated minerals include small zircon crystals, fergusonite, columbite-tantalite, spessartite garnet, pyrite, zoisite, thulite, and rhabdophane (pseudomorphs after blades similar in habit to allanite). Jahns (written communication, 1966) reported gadolinite from the mine. The geology of the deposit has been described by Griffitts and others (1953, p. 186).

Fairfax County, Potomac River gorge near Washington, D. C. Reed and Jolly (1963, p. 10) have reported allanite in quartz veins in the Potomac River gorge. According to Jolly (written communication, 1966) the mineral occurs only as microscopic grains, often as cores in yellowish epidote crystals. Similar allanite occurs in the chlorite-muscovite gneiss in the area. It is in mica as small reddish grains surrounded by radiogenic halos, and also as cores of epidote grains (Reed and Jolly, 1963, p. 8).

Fauquier County, near Markham*. Watson (1917) mentioned allanite in Fauquier County, but did not describe the mineral or the occurrence. The writer was unsuccessful in his attempts to locate the deposit, however, he did obtain two small specimens from the U. S. National Museum. These are labelled "Markham, Fauquier County" (USNM 68661) and "Fauquier County" (USNM 104524). The specimens were broken from larger masses of allanite. They are black, pitchy, and show thin brownish alteration crusts.

Franklin County*. Watson (1917) stated he examined a piece of allanite reported to have come from Franklin County. The specimen was not described. A small pitchy Watson allanite specimen (V2980d) in Lewis Brooks Museum was labelled "22% Ce_2O_3, C. D. Haislip, Booneville, Franklin County." No doubt the address should have been Boones Mill. This town is located near the Roanoke County, Shepherd's farm deposit, and there is a possibility the specimen is from there. However, the analysis does not agree with that for the Shepherd's farm allanite (Watson, 1917).

Henry County, Ridgeway-Sandy Ridge pegmatite district. Griffitts and others (1953, p. 145) suggest the occurrence of allanite in the Ridgeway-Sandy Ridge pegmatite district which includes Henry County, Virginia, and part of North Carolina. However, the only allanite described is in the Knight pegmatite in North Carolina, not far from the Virginia line.

According to Jolly (written communication, 1966) in 1949 Houk, of the U. S. Bureau of Mines, found weathered allanite at the Samuel Amos prospect which is at Chestnut Knob, a small community about 4 miles northwest of Ridgeway. Thorium mineralization was also reported in the Garret prospect about half a mile west of the Chestnut Knob Baptist Church.

Loudoun County, west of Aldie. An epidote granite from 3 miles west of Aldie, described by Keith (1894, p. 300), contains quartz, plagioclase, orthoclase, biotite, chlorite, magnetite, epidote, and possibly allanite.

Louisa County, old Sulphur mine near Mineral. Allanite occurs as minute (0. 5 mm) crystals in schist at the old Sulphur mine near Mineral. Katz (1961, p. 69) has described the mineral in detail. Most of the allanite occurs at the centers of zoned crystals, where clinozoisite surrounds the allanite in continuous crystallographic orientation and this in turn is surrounded by an outer zone of epidote in parallel orientation. Sometimes only one or perhaps none of the latter minerals surround the allanite. Most of the allanite is metamict, as indicated by optical data and radial fractures in the minerals which enclose the allanite, e. g., garnet and hornblende. Intense radiogenic halos surround the allanite in hornblende and chlorite. Poorly developed polysynthetic twinning was observed for some of the crystals.

Nelson County, near Arrington. Good specimens of allanite have been obtained near Arrington according to Dana (1895, p. 1072). This may be a general reference to one of the more specific localities described in this paper.

Nelson County, east of Lowesville. Memminger (1885) analyzed allanite from "about three miles east of Lowesville, Nelson County." The allanite occurred as detached masses associated with clay in a weathered pegmatite. The rounded allanite masses are covered with a thin yellowish-white coating. Valentine (1885) analyzed the material formed by weathering and briefly described its properties. The writer was not able to relocate the deposit, nor was he able to find museum specimens to study.

Nelson County, west of Massies Mill*. According to Paschal (oral communication, 1964) there is a deposit of allanite on Priest Mountain south of State Highway 56 between Massies Mill and Crabtree Falls. The writer was unsuccessful in his attempts to find the deposit, but a specimen of the mineral was available for study. The black pitchy mineral is massive and deeply weathered to a brown earthy crust.

Nelson County, Roseland district. According to Herz (written communication, 1966), allanite inclusions measuring from about 0. 1 to 0. 3 mm occur within epidote grains about 0. 2 mm by 0. 7 mm in a poorly foliated granitic rock near the southeastern corner of the Piney River quadrangle in the Roseland district. Other minerals in the rock are coarse grained plagioclase, biotite, clinozoisite-epdiote, quartz, and sericite. The allanite is pleochroic from a deep yellowish brown to a paler yellowish brown; and isotropic areas, assumed to be metamict, are found in the centers, or near the peripheries, of most grains.

Page County, near Marksville*. Allanite has been reported at the Owen prospect 3 miles southeast of Marksville by Sanford and Stone (1914, p. 191). Watson (1917) further indicates the allanite is associated with titaniferous magnetite in a pegmatite in quartz-bearing hypersthene syenite. The allanite is weathered to the usual reddish-brown crust, which is coated by a thin outer light-colored layer. The writer was unsuccessful at locating the deposit, but he did obtain a small fragment from the U. S. National Museum (USNM 94737) which meets the above description.

Patrick County. A piece of allanite reported to have come from Patrick County was examined by Watson (1917). The material was not described, and no further information on the locality has been found.

Roanoke County, the old Shepherd farm, crest of Blue Ridge*. This locality, not far from the G. S. Hofawger home which is east of U. S. Highway 220 at the end of State Road 921, was first described by Watson (1917). Numerous weathered allanite masses, up to 6 inches across, occur in a greatly weathered zoned pegmatite, with kaolinized feldspar, quartz, weathered dark-colored mica (large books and schistose masses), epidote, single-crystal magnetite masses (up to 4 inches across with excellent parting), zircon crystals, thorogummite, and anatase pseudomorphs after sphene crystals (Mitchell, 1964). Small strongly radioactive waxy-yellow inclusions in some of the allanite give X-ray patterns close to thorianite, with a = 5.54 Å (after heating for an hour at 800° C). Chemical analyses of both the fresh and decomposed allanite have been given by Watson (1917). An X-ray analysis of the red-brown alteration crust by the writer only showed nearly amorphous goethite.

A small, much less weathered allanite-bearing pegmatite occurs on the trail below the main deposit. Additional minerals encountered here include ilmenite, apatite, arsenopyrite, amphibole, and garnet.

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